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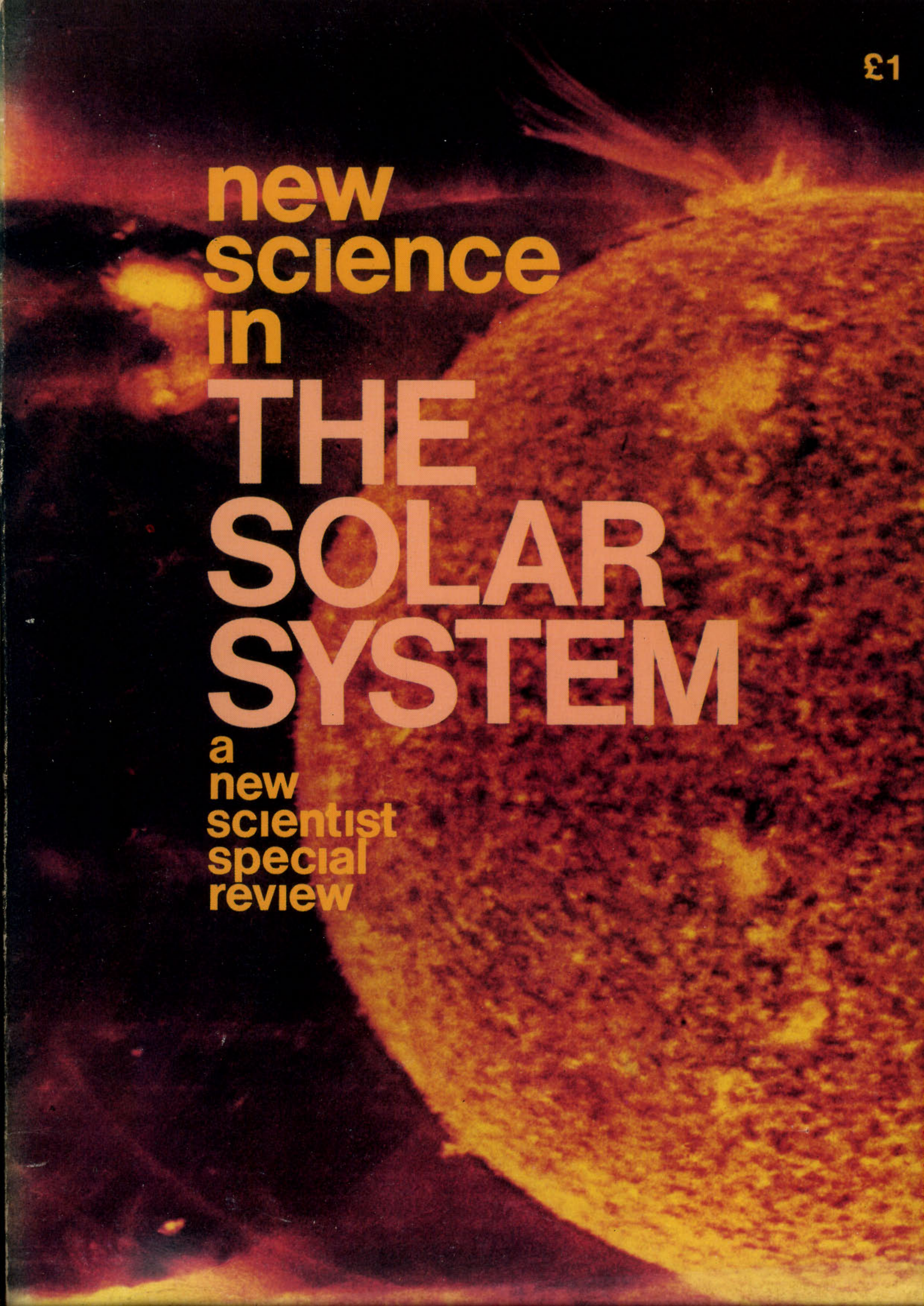
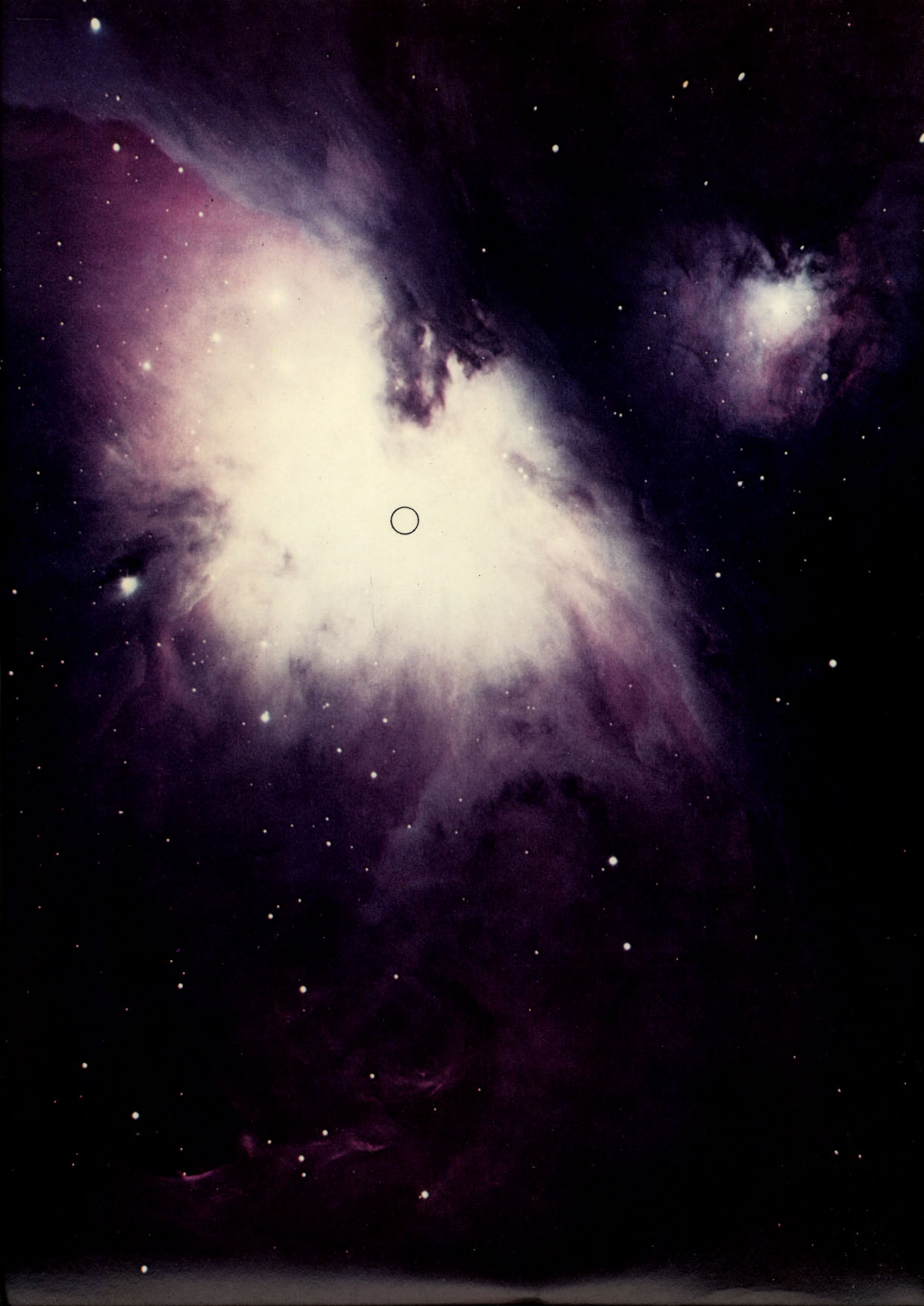
new science in THE SOLAR SYSTEM

a new scientist special review





NEW SCIENCE IN THE SOLAR SYSTEM

Editor: Dr Peter Stubbs. Design and Production: Margaret Webb. Maps and Diagrams: Neil Hyslop.

Front cover: This Skylab picture of the solar disc shows a spikey eruption projecting a million miles up into the solar corona. The "false" colours represent X-ray temperatures determined by the Marshall Space Flight Center's SO56 X-ray Telescope

Inside front cover: The Great Nebula in Orion M42 and its smaller companion M43 form a pair of emission nebulae (HII regions) which radiate strongly in the infrared. The hatched disc encompasses a complex of infrared sources. Are such highly reddened point sources, optically invisible, true protostars and even planetary systems? (Hale Observatories photograph)

Inside back cover: Looking back toward the lunar surface module during Apollo 14. The tracks of the astronauts' handcart can be seen in the foreground

Acknowledgement: All photographs in this publication are by courtesy of NASA, unless otherwise specified

The past few years, and 1974 in particular, have provided us with a truly astonishing new picture of the planetary system in which we live. These revelations about our space neighbours are almost entirely due to the outstanding successes of NASA's planetary programme, and to a lesser extent those of Soviet space scientists. The present is a good moment to take stock of what we have learnt about the solar system during the space age. 1974 marks, in a sense, the completion of the preliminary round of planetary exploration. The past 12 months have seen the first visits by spacecraft to Jupiter, Mercury and Venus, and the first manned space observations of the Sun aboard Skylab. Spacecraft have now taken a thorough first look at all the more accessible bodies in the solar system and, after Mariner 10 returns once more to Mercury in March 1975, there will be a hiatus until 1976 when the first Viking lander arrives on Mars. Our initial close-up examination of the next planet to be reached by a spaceprobe must wait, however, until 1979 when Pioneer 11 gets to Saturn. The outer planets call for even longer time scales. The new knowledge we have gleaned about the inner five members of the solar system and the Moon is, by contrast with our comparative ignorance six or seven years ago, extensive.

Much of this new information may rightly be classed under the old fashioned heading of 'general knowledge', that is, knowledge about the human environment as relevant as the broad facts of geography, history, or biology. In this brief publication I have tried to gather together some of the essentials of the emerging picture of the planets. It is impossible to be comprehensive. The scientific literature burgeons with papers on new aspects of the solar system. Here , only a small fraction of solar research in the space age is represented (partly because it more properly belongs to stellar, than planetary, science); the exciting developments relating to the natural satellites of the major planets are merely touched upon; and the articles dealing with the planets themselves are necessarily only brief summaries.

The bodies which planetologists have studied so far and which are represented here, fall into two empirical categories — those of predominantly geological interest; and those with dense, all-obscuring atmospheres whose meteorology is a prime concern. Mercury, Earth, the Moon, and Mars fall into the first category. Venus, Jupiter, and the other major planets fall into the second. It seems unlikely that we shall ever learn as much about the surface of Venus, for example, as we already know about those of Mercury or Mars. Above these considerations, though, is the astrophysical aspect of the planets — the significance of their shape, the nature of their interiors, their composition, and their interactions with the solar wind and with energetic particles. The discovery of a magnetic field on Mercury is, for instance, germane to some of these problems; while the Jovian magnetic field, now delimited by Pioneers 10 and 11, has for several years conditioned the thoughts of planetary astrophysicists.

Even half a millenium after Copernicus laid the foundations of modern planetary research there is still a great deal to learn about the origin of the solar system. NASA's missions have established that the spectacular technology is now to hand which can provide at least some of the answers to the relevant profound questions.

PETER STUBBS

COSMOGONY NOW

JON DARIUS

Most astronomers think that first there is the solar system, then the physics of the solar system, and next speculation, then wild speculation, and finally there is cosmogony, if I may paraphrase R. Craft's gentle mockery of solar-wind physics. Cosmogony, the study of the origin of the solar system, demands the willing suspension of disbelief no less than literary fiction.

How are we to interpret the bewildering fact that there are as many hypotheses as there are investigators — indeed more — and that far from approaching a gradual consensus, their views are diverging more today than ever before? They agree with H. C. Urey that condensation of a planet directly from the solar nebula without a solid accretion stage is out of the question; that the Sun did not go through a superluminous phase as once believed; that the final gravity-dominated era of accretion lasted only a few thousand years at most — and precious little else!

One reason for the widespread discord is that observational data which would otherwise bridle the more unruly theories are sadly lacking, and the few items we know are susceptible of multiple interpretation. Observations of the 2·76 K microwave background and the cosmic helium abundance, among others, suggest that we are in a better position at present to probe the birth of the universe than that of the solar system! Cosmologists might not have the edge on cosmogonists for much longer, however; vital fresh data from interplanetary probes as well as independent advances in gas-cloud dynamics, plasma chemistry, and the mechanics of particle impact, will consign more than a few pet theories to the round file.

Is the alleged dearth of empirical data not an exaggeration? After all, the orbital elements and physico-chemical properties of solar-system bodies must provide a clue to their genesis. Where's the rub?

TOO MANY ALTERNATIVES

The rubs are two. One is that cosmogonic models are generally not unique, so that a plethora of equally plausible causes could have engendered some observed effect. For instance, the asteroids could be shards of a single fragmented planet — a rather unfashionable theory today. On the other hand, H. Alfvén has shown that they could well represent a planet in its formative period, longer than for other planets because the smeared-out mass density in the asteroidal belt is orders of magnitude lower than that of any other planet except perhaps Pluto. Then again, maybe the rate of destructive processes tending to dispersion has overtaken the rate of constructive processes tending to accretion, as in G. P. Kuiper's model of several planetoids which collided and broke up.

The second rub is that the clues are really too numerous, not too few. Which are relevant? Is it imperative that our cosmogonic model be able to account for Saturn's rings — or are they simply the residue of a moon that strayed too close and split asunder inside the Roche limit? For the exceptionally high inclination of Uranus' equator to its orbit (98°) — or is this the accidental by-product of an impacting body well after the cosmogonic era? For the formation of the Sun — or had the Sun already formed by the time solid planetesimals (embryos) began to accrete, some 4500 to 4700 million years ago?

In historical perspective, two types of cosmogonic hypothesis have been advanced: catastrophic and evolutionary. If the catastrophists are right, then the solar system is a unique accident or at least a *rara avis* borne of a freak concatenation of circumstances. Two theories early in this century called for a chance encounter between our Sun and another star: the Chamberlin-Moulton hypothesis wrenched a tidal filament from the Sun, while the Jeans-Jeffreys hypothesis snatched its gaseous filament in a grazing encounter. These hypotheses are doomed not just by the improbability of encounter, but by physical law. L. Spitzer showed that the hot gas pulled out of the Sun would rapidly disperse, and F. Nölke proved that filaments would have to be as massive as the Sun itself if they were to be proof against tidal disruption. A latter-day catastrophist, M. M. Woolfson, has revived the notion of stellar encounter with a novel twist: the Sun tears material out of a light star in a rapid encounter, perhaps as a member of a young star cluster now dispersed.

PLANETS ELSEWHERE

Stellar encounter is frightfully improbable (less so in a cluster), but admittedly a finite possibility exists. Without rejecting out of hand the possibility that the solar system — and consequently our very existence — is merely one of Nature's vagaries, we must regard all such theories with suspicion. Catastrophe — accident, if you like — is the last refuge of the perplexed theorist.

Whether planetary systems occur in the natural course of stellar evolution, or whether ours is a gross abnormality, need not be an academic question. Categorical proof that a single other such system exists in the solar vicinity would quite confute the catastrophists. The most promising, albeit controversial, candidate for a planetary system is afforded by our second closest stellar neighbour (after the Alpha Centauri system): Barnard's star, 6 light-years distant. Analysis of several decades of proper-motion data by P. van de Kamp has confirmed a wobble in its motion which must be due to an invisible perturbing companion, conceivably a Jovian-type planet in eccentric orbit, or else two in coplanar orbits, or even (according to an interpretation by D. C. Black and G. C. J. Suffolk) a *minimum* of two massive planets in highly inclined, closely spaced orbits. On the same basis, van de Kamp has very recently proposed a planetary companion twice as massive as Jupiter for Epsilon Eridani (ninth nearest neighbour). The evidence is suggestive, but scarcely compelling.

Infrared astronomers have culled several tantalising objects which may represent planetary systems at the earliest stage — objects cloaked in gas and dust that just may be protostars. (Reddening by interstellar matter as opposed to a circumstellar dust shell is not wholly ruled out, though.) Preplanetary material may be present in the small, fluctuating nebulae known as Herbig-Haro objects and in the related cocoon nebulae as well, which apparently provide us with a flashback to our solar nebula at 5000 million years' remove. Half a dozen

infrared stars embedded in cocoon nebulae are recognised, of which FU Orionis and V 1057 Cygni are famous for their abrupt brightening, interpreted by some as a reduction in the opacity of the nebular material as it collapses to a disc. Point sources in the Cone Nebula in Monoceros and the Orion Nebula (see inside front cover) may be even younger, while the variable, strongly magnetic T Tauri stars (Plate 3), and perhaps also the compact dust concentrations called Bok globules (Plate 4) could represent a later phase. If such objects do provide cosmic snapshots of regular stages in preplanetary evolution, then cataclysmic theories must go the way of the dinosaurs.

Cosmogony *now* must forego the 20th-century classics like Kuiper, von Weiszäcker, or Whipple. Contemporary work still draws heavily on such forerunners, of course, largely because any credible cosmogony must come to grips with the same problems — and these are severe.

THE TASK IS HERCULEAN

Assembling a planetary system, even on paper, is a daunting task. Suppose you wish to construct your own model. Start with a spherical cloud of dust and plasma (a mixture of neutral and ionised gas) and persuade it to collapse to a nebular disc. Whether a stellar condensation lies at the centre of the disc or is going to be formed out of it is a moot point. Then try to vault three challenging, potentially lethal hurdles, termed by H. Reeves: 1) the thermal barrier — gravity must win the tussle with random thermal motion; 2) the magnetic field barrier — the contracting cloud must overcome the magnetic lines of force effectively frozen into the plasma; and 3) the angular momentum barrier — somehow enough angular momentum must be disposed of so that collapse does not lead to disruptive rotational instability. Now make sure that the temperature, density, and velocity profiles in your nebula will be appropriate for gas condensation and particle accretion consistent with the surface and interior composition of bodies in the solar system today. You must also dream up the actual mechanisms which metamorphose plasma and dust into planets, and if they sound bizarre (collisions of grains coated with sticky organic molecules) or naïve (cold welding *in vacuo*), you are in good company! At typical densities assumed for the disc of the solar nebula, perhaps a million atoms per cubic centimetre, particle encounters will be so rare that they had better stick, not rebound, when they do collide — or else you will end up proving that we do not (yet) exist. Think of this latter problem as a fourth hurdle, the time barrier: your model must be churning out members of the planetary system fast enough to beat the deadline at 4500 million years BC when the Earth had become a solid planet, not a floccule or a swarm or a condensing ring.

Now apply the acid test: how close does your model approach reality? Does it mimic the observed distance and mass distribution? Did your planets father satellite families, or adopt them by orbital capture? Are most of your orbits coplanar, concentric, virtually circular, and direct, in the same direction as the Sun's rotation? Do your orbiting bodies rotate at a rate almost independent of size (save those locked in spin-orbit resonance) — an axial spin period P of 9 hours, give or take a factor of 2? This latter property, usually dignified by the phrase "isochronism of spin", is one of the most astonishing features of our system. Certainly P is not numerically constant, ranging from 2·3 hr for the smallest body of measurable spin (the asteroid Icarus) to 9·8 hr for the largest (Jupiter) and 24·6 hr for Mars. Yet a mere factor of 10 in P covers a mass range from 10^{16} to 10^{30} g (a ratio of 100 million million)! Last, and perhaps most important, are these the right questions, the essential constraints? After all, with but one example before our eyes, we can only make educated guesses at those properties of the solar system which are *sui generis* and those which planetary systems throughout the Galaxy — if indeed there are any others — can be expected to possess.

Let us sample the work of just a few of the more recent evolutionists to enter the lists. In D. G. King-Hele's droll classification, they fall into two categories, dustmen and electricians, according as they are concerned chiefly with particle dynamics or with hydromagnetic effects. The earliest stage in the scenario of dustman A. G. W. Cameron pictures a uniformly rotating solar nebula of twice the Sun's mass, half of which is destined to be blown out of the system by the primaeval solar wind, more like a gale. (This "gale" is corroborated by observations of extensive mass loss from T Tauri objects.) Contrary to any other evolutionist, Cameron does not posit a high-density protosolar blob at the centre; instead, the density diminishes smoothly outward. The central star condenses as the nebula evolves, abetted by convection currents which lead to inward dissipation of gas on a time scale of a few thousand years. As the turbulent cloud collapses under gravity, grains collide and stick (by supposition!) to form icy iron-silicate basketballs in the outer shell of the cloud where the temperature is low enough to prevent evaporation of the ice. In only a few centuries the solid bodies will have settled toward the plane of rotation, where planetary growth by accretion proceeds at a phenomenal rate. Past a critical radius, the rate of random collisions is overtaken by that of gravitational capture, and in a few thousand years the planetary system will have formed, possibly even before the Sun itself! In Cameron's model as in V. S. Safronov's below, gaseous giants like Jupiter and Saturn require accretion of gas about a solid core of several times the Earth's mass, while satellites arise from capture or from sub-discs around the planets which duplicate in miniature the main disc about the protosun. Cameron's comets originate in "satellite" discs at great distances — a neater solution than ejecting them from the inner solar system, as in Safronov's scenario.

A SOVIET DUSTMAN

Chief spokesman for the Soviet school of cosmogony descended from O. Yu. Schmidt, Safronov has independently arrived at a picture not dissimilar to Cameron's, although differing in detail. Safronov's model cunningly ignores the origin of the nebula about the central star, and focuses at once on the infall of dust to a disc in the equatorial plane, which takes 10 to 100 times longer than in Cameron's scheme. A word of warning: partisans of "disc" models are not to be trusted — both Cameron and Safronov in fact envisage a disc where thickness increases with distance, in cross-section more like a bow-tie than a pancake. But whereas Cameron demands violent turbulence to increase the probability of encounters, Safronov requires damping of turbulent motion within a few rotations. Gravitational instability he has shown to be inoperative in the gas, but effective as a mechanism of coalescence in the dust, except in the innermost region where thermal effects from the Sun override it. (Mercury must

have grown directly through particle accumulation.)

Safronov and R. T. Giuli have independently posited the accretion of grains impacting on growing embryos to account for planetary rotation. Superimposed on the regular rotational component imparted to all solar system bodies is a random component which could account for inclination of axis to orbit.

Another dustman ought to be mentioned here, for although his model is far less sophisticated, S. H. Dole has created quite a stir in cosmogonic circles. In a computer simulation, a particulate nucleus is injected into the solar nebula, this time with the Sun already formed, and allowed to sweep up all the dust it meets. Then another is randomly injected in the same plane to do likewise, with the proviso that a collision with the first will result in coalescence. The process continues until all the dust in the nebula is consumed. Some of his net products resemble the real solar system to a remarkable degree.

INGENIOUS ELECTRICIANS

As representatives of the "electricians", H. Alfvén and G. Arrhenius — plasma physicist and cosmochemist respectively — have scored some remarkable successes with their account of the so-called "hetegonic" process even if it remains rabidly controversial. Instead of tackling the problem of satellite formation after dealing with the planets, they treat the more general case of the evolution of a secondary body in the electromagnetic and gravitational field of a primary. At the outset, the Sun is presumed already extant, and an interstellar cloud is drawn sunward in small doses over 10 to 100 million years. When the neutral gas reaches a certain critical velocity whose value depends on the particular element, it ionises and, virtually trapped by solar magnetic field lines, begins to corotate with the Sun. Angular momentum is transferred hydromagnetically from central body to partially corotating plasma. Grain formation will occur by processes of plasma chemistry not remotely similar to normal terrestrial chemistry; at very low densities in the absence of thermal equilibrium, crystals can condense directly out of the plasma. Thus chemical speciation occurs *ab initio* in two ways, one connected with different stopping distances of infalling matter, the other with precipitation at various temperatures and pressures. Evidence from those most ancient meteorites, the carbonaceous chondrites, points to onset of grain precipitation at 5000 K in the plasma and 100 K in the grains. Condensation on the solid grains is followed by coagulation to embryos, and eventually by cold accretion (with strong local impact heating) to planets or satellites. Isochronism of spin follows naturally from the fact that the accretion process is independent of size.

At the embryonic stage, most theories look stark ignorant — or as H. Reeves wryly puts it, they bear "a definite resemblance to the writing of the mediaeval alchemists." Exactly how does the theorist propose to effect embryonic accretion when grains typically collide at relative velocities of 1 to 10 km/s? Alfvén's solution is not merely the ubiquitous "cold welding" invoked by so many other authors without regard to relative velocity; rather he claims that the hypervelocity impact *will* cause fragmentation, but that the fragments of both bodies should eventually coalesce, not disperse. The stream of orbiting particles will return to the point of impact, perturbations aside, and, as long as inelastic collisions dominate over dispersive forces, the stream will contract and thus encourage accretion of its constituent grains. These "jet streams" occur as a result of the focusing effect of a gravitational field on small orbiting particles, the argument runs; its conviction, though, comes less from the qualitative argument, than from the discovery of some 10 jet streams (or something akin) in the solar system today — loose asteroidal families with all five orbital elements similar.

Of course, the sheer fact that stream members will have low relative velocities does not account for the *mechanism* of accretion. This is Arrhenius' province, and he has demonstrated from studies of lunar soil that grains aggregate through electrostatic attraction to asymmetric fluffy clusters of low surface area; but just what would happen in a hypervelocity impact remains to be investigated.

Sherlock Holmes was no doubt right to declare, "It is a capital mistake to theorise before one has data." Yet although there are good grounds for seeking more data, the chief problem lies in knowing how to interpret such data as we have already amassed. These data come primarily not from planetary surfaces, where endogenic processes like volcanism and exogenic processes like meteoritic impacts have blurred or erased all primaeval information, but from meteorites, especially the chondrites (Plates 1 and 2).

The composition of these ancient stony meteorites has been construed as a record of the temperature and pressure régime which dictated the sequence of condensation in the early accretional era. E. Anders, J. W. Larimer, and many others have accordingly "read" the cosmothermometers and cosmobarometers — for example, the proportion of volatile metals like bismuth and thallium. But such cosmochronology depends crucially on one precarious assumption: thermodynamic equilibrium between solar nebula and condensates. Until divergent opinions on that issue have been reconciled, inferences about the nascent solar system belong to Tennyson's "fairy tales of science".

COOLING IN EQUILIBRIUM

All the same, a good word must be said for the early success of a gratifyingly simple model recently explored by J. S. Lewis. Predicated on a *slow* rate of cooling in the solar nebula with gradual radial falloff in temperature, it envisages condensation of gas to grains in a state of chemical equilibrium. Rapid cooling would prevent diffusion (thereby inhibiting a wealth of potential chemical reactions) and lead to inhomogeneous accretion of "onion rings" of different elements; slow cooling, on the other hand, leads to chemical homogeneity as found in the primitive chondrites. In large bodies chemical differentiation will take place inside the protoplanet through sinking of denser and rising of lighter components. Mariner 10 photographs of Mercury showing mare-type material (implying lava flooding), along with the planet's high bulk density, are entirely consistent with the silicate mantle and thick iron core predicted by the equilibrium-condensation model. A mission to the moons of Jupiter would firmly substantiate or discredit Lewis's model.

This overview of the prevailing discord in cosmogony today must sound unduly pessimistic. Proponents of one theory utter philippics against rival cosmogonies, accuse them of numerology or alchemy; yet they dogmatically defend their own fantasies. Considering the oracular nature of so many cosmogonic hypotheses, W. H. McCrea once dubbed them "virtual election manifestos." Until the pertinent facts become clearer, one would not want to lay odds on victory at the polls.

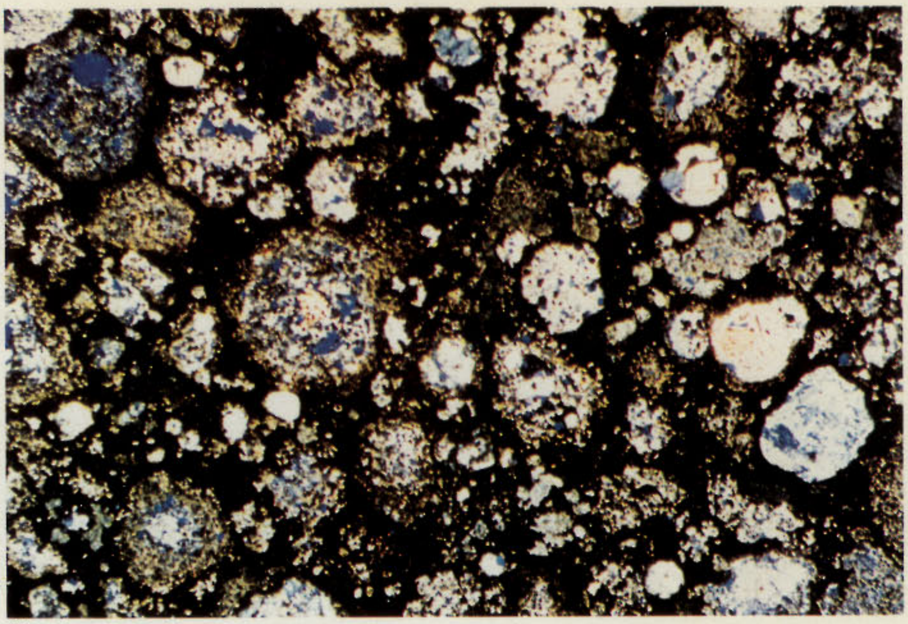


Plate 1

Plate 2

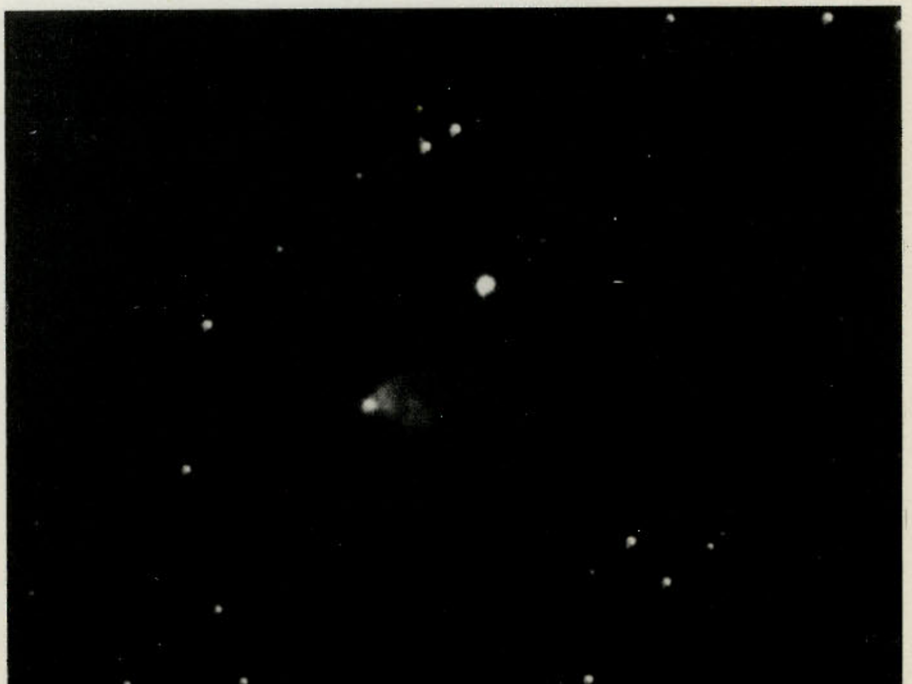


Plate 3

Plate 1 Chondrites are stony meteorites in most of which solid silicate droplets called chondrules are embedded in a fine-grained matrix. In the 12× microphotograph in polarised light of a thin section of the C3 carbonaceous chondrite Allende, studded with round chondrules, opaque minerals show up blue or black, transparent ones white. It is only slightly metamorphosed from the solar nebula of dust and gas out of which the solar system formed. (Courtesy of T. E. Bunch, NASA-Ames Research Center)

Plate 2 The Orgueil meteorite, a black and easily crumbled C1 chondrite, is an even purer sample of primordial material. Characterised by high volatile content and low density, a C1 chondrite paradoxically contains *no* chondrules. Surprisingly, Orgueil does contain organic compounds comprised not only of contaminates since its fall in France in 1864 but of amino acids, purines, and pyrimidines of extraterrestrial, abiotic origin. (By permission of the Trustees of the British Museum Natural History)

Plate 3 R Monocerotis, or Hubble's Variable Nebula is an object 4 or 5 times as massive as the Sun with a dust-enshrouded central exciting source at a temperature of 10 000 K. One of the foremost candidates for a protostar, it is probably the precursor of a T Tauri star, whose characteristic infrared emission and irregular variability it already displays. Some of the circumstellar matter is bound to be ejected from the system, but a fraction of it may become source material for the genesis of a planetary system. (Courtesy of University of London Observatory)

Plate 4

Plate 4 Like black flyspecks against the luminous background of emission nebula IC2294 in the southern Milky Way, Bok gloules may figure somewhere in the sequence of planetary evolution. V. C. Reddish, the new Astronomer Royal for Scotland, Speculates that they represent the earliest protostars, while American astronomer G. H. Herbig believes they mark a stage of nebular, rather than stellar and planetary, evolution. (Cerro Tololo photograph courtesy of B. J. Bok)

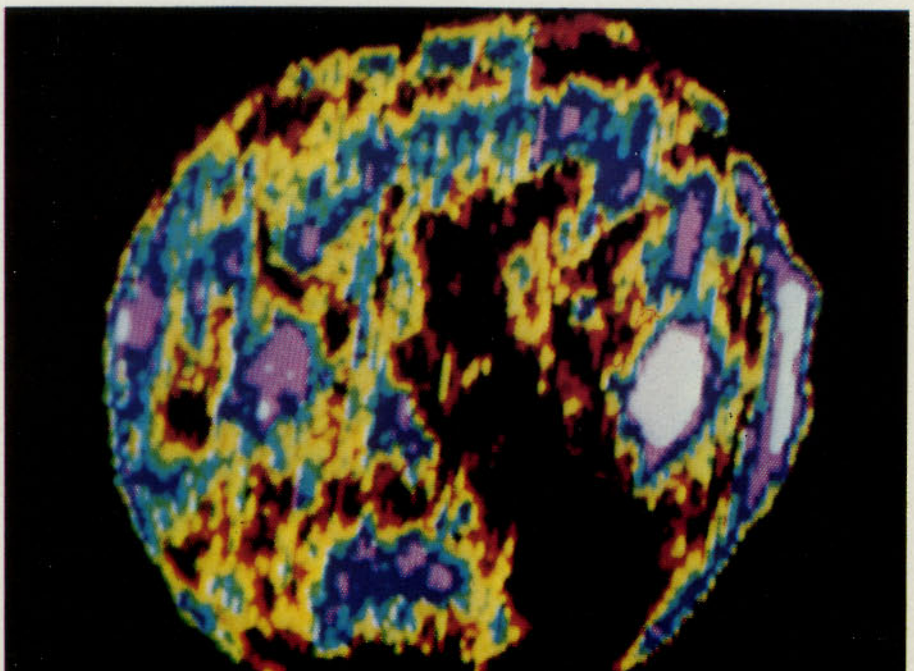


Plate 5

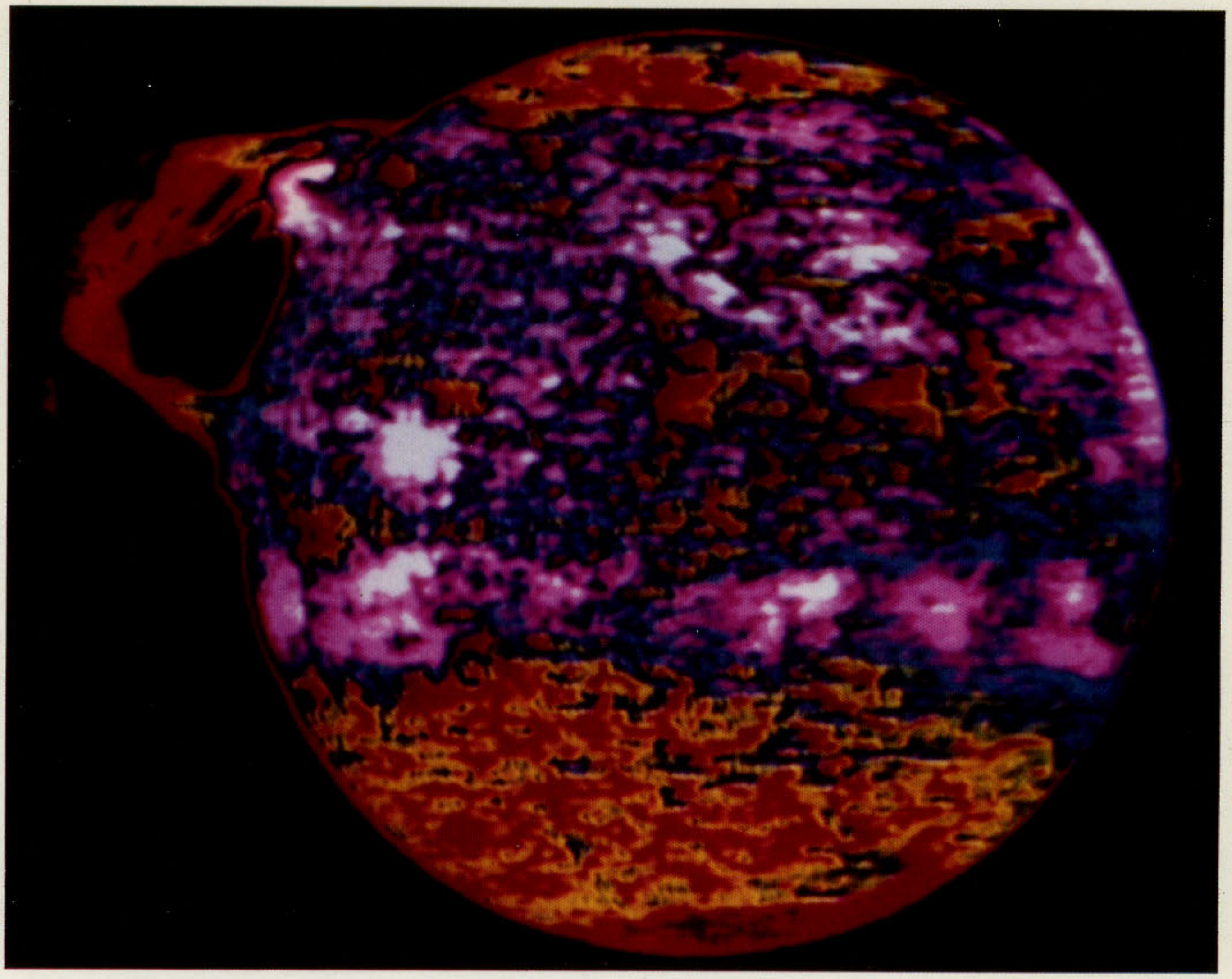


Plate 6

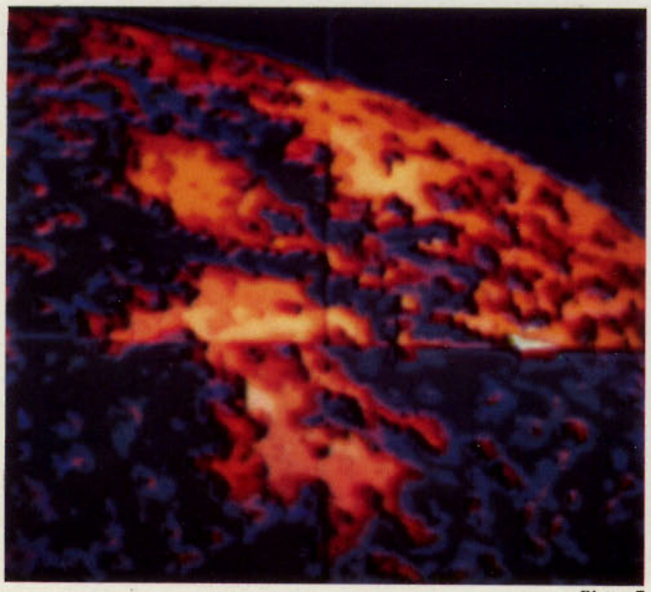


Plate 7

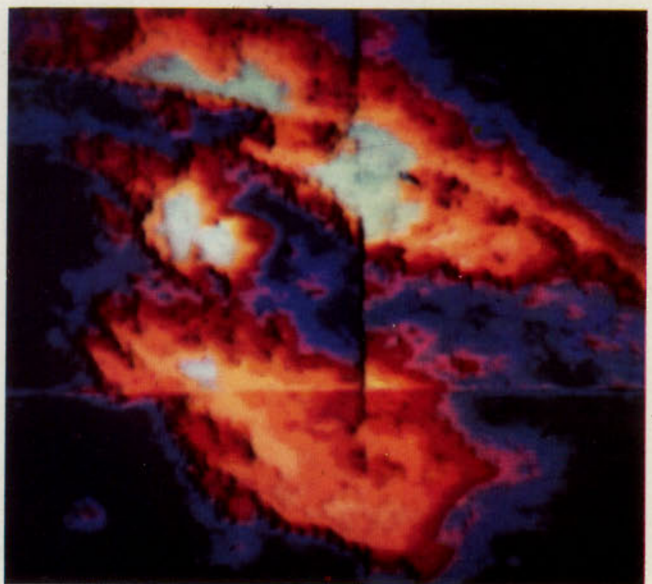


Plate 8

Plate 5 A "false colour" extreme ultraviolet shot of the Sun showing a large coronal hole. Skylab facilities enabled the astronauts to study changes in such patterns on a day-to-day basis

Plate 6 Skylab astronauts photographed this huge solar eruption on 19 December 1973. The picture was taken with the US Naval Research Laboratory/Ball Brothers Research SO82A extreme ultraviolet spectroheliograph. The colours are "false colour" representing the degree of solar intensity from red, through yellow and blue, to purple and white where the activity is most intense (NRL/NASA)

Plates 7 & 8 Two false-colour photographs of a group of solar active regions taken from Skylab with the Harvard College Observatory's far ultraviolet spectroheliometer. The picture on the left is in CIII light at 977 angstroms, and represents the upper chromosphere; that to the right of it in MgX light at 625 angstroms represents activity in the transition region. The photographs were constructed from video data by Colorado Video Inc. (Photo: Harvard College Observatory)

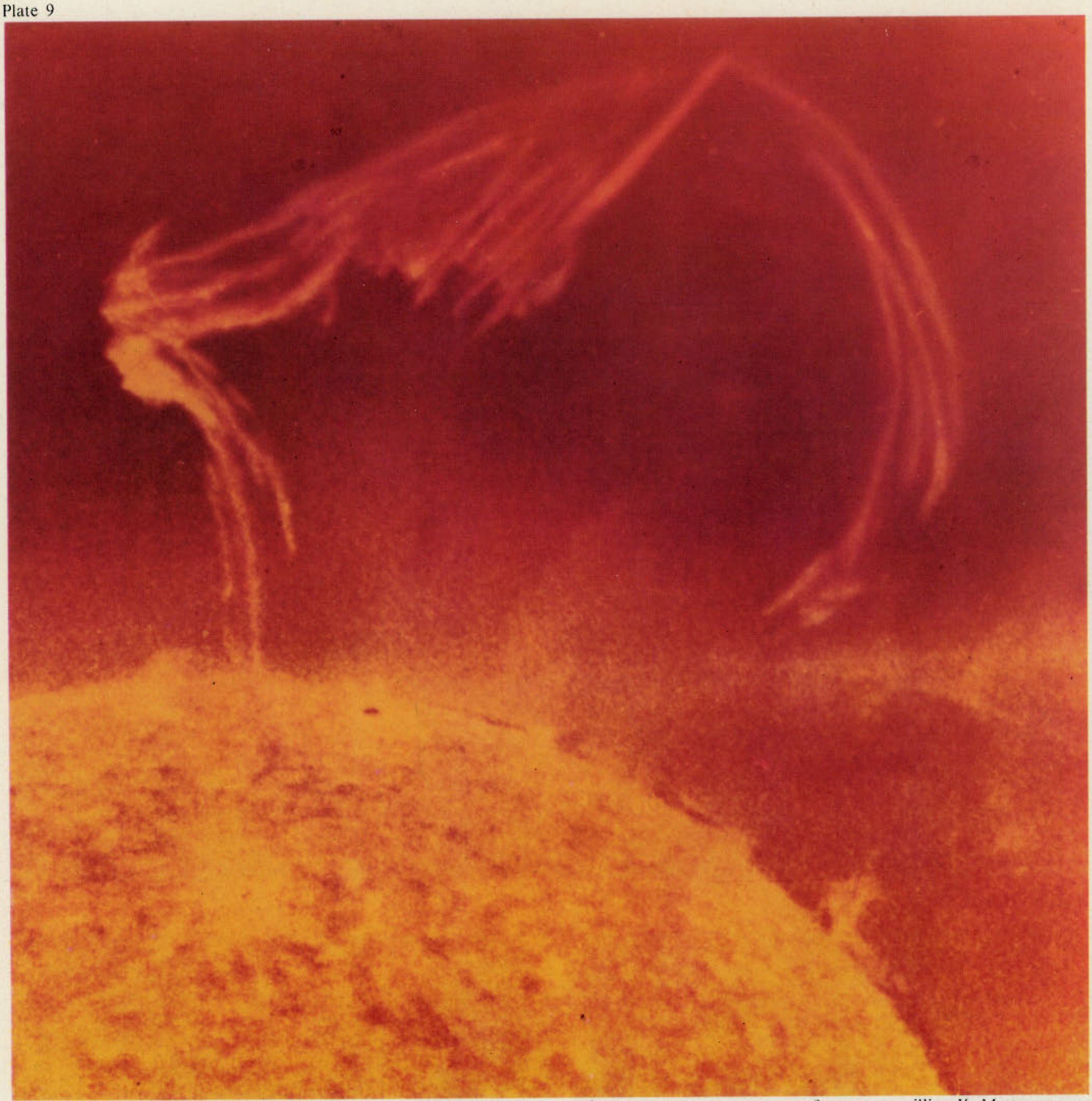


Plate 9 A spectacular, and baffling, solar eruption 800 000 km high photographed in ionised helium light by the Naval Research Laboratory/Ball Brothers Research spectroheliograph aboard Skylab. "Cool" helium gas at some 50 000 K is here being injected into the solar corona at a temperature of some two million K. Matter appears to be being reflected back to the Sun's surface from the apex of the arching structure but magnetic field/plasma interactions are alone inadequate to account for what is happening (Photo: NRL/NASA)

ATM SOLAR INSTRUMENT SUMMARY

Instrument	Sponsor	Spectral coverage (angstroms)	Solar region observed	Spatial resolution (arc seconds)	Spectral resolution (angstroms)	Maximum picture rate (per min)	Data form*
X-ray telescope	American Science and Engineering Company	3–60	corona (1–$1{\cdot}5R_{\odot}$)	2	0·15	96	70-mm film 5 cameras 7000 frames each
X-ray telescope	NASA Marshall Spaceflight Center	6–33	low corona	2·5	2·5	77	35-mm film 5 cameras 7200 frames each
XUV spectro-heliograph	US Naval Research Laboratory	150–615	chromosphere	5	0·13	1	35-mm film 6 cameras 200 strip frames each
UV spectro-heliometer	Harvard College Observatory	300–1400	chromosphere	5	1·2	9 lines	photoelectric, digital data
UV spectrograph	US Naval Research Laboratory	970–3940	chromosphere	3	0·08	4	35-mm film 4 cameras 1600 frames each
White light coronagraph	High Altitude Observatory	3500–7000	outer corona ($1{\cdot}5$–$6R_{\odot}$)	8	broad band	4	35-mm film 5 cameras 8000 frames each
Hα telescope	Harvard College Observatory	6563	low chromosphere	1	0·7	4	35-mm film 5 cameras 16 000 frames each

*Not all frames were expended in each camera

THE SUN FROM SKYLAB

JOHN EDDY

The phenomenal success of the Apollo Telescope Mount (ATM) solar experiment on Skylab was more than a milestone in space exploration, and more than an epoch in solar physics. It probably heralds an approaching era of further coordinated onslaughts — not only in the study of the Sun, where they now seem highly effective, but in other areas of astronomy as well. For solar physics traditionally leads astronomy in the methodology of research. To the romantics among us — and I am one — the Skylab success may not seem a wholly pleasant victory. The ATM succeeded in large measure by impersonalising astronomy — replacing single efforts and more limited crusades with the staggering power of regimented attack. Skylab seized the remaining momentum and paraphernalia of the Apollo lunar programme and applied it to loft a battery of the world's most advanced solar telescopes to the ideal observing site; then, from an extensive ground control centre manned by professional astronomers and supported by observatories around the world, the ATM team collectively directed their instruments with careful strategy and unerring aim. This intensive effort was maintained for more than eight months, from 28 May 1973 until 8 February 1974 when the departing third Skylab crew turned off the solar console for the last time.

THE EXPERIMENTS

The main solar instruments of ATM are described in the Table. With the exception of two Hα telescopes, which were carried for auxiliary use, each ATM instrument performed observations not possible from the ground. Spectral coverage was concentrated in energetic, short wavelengths which are not transmitted through the Earth's atmosphere. Previous rocket and satellite observations have demonstrated the value of studying the Sun in the ultraviolet and X-ray spectrum; solar radiation of these wavelengths originates above the photosphere in the Sun's more active and dynamic upper atmosphere — the chromosphere, the lower corona, and their transition region.

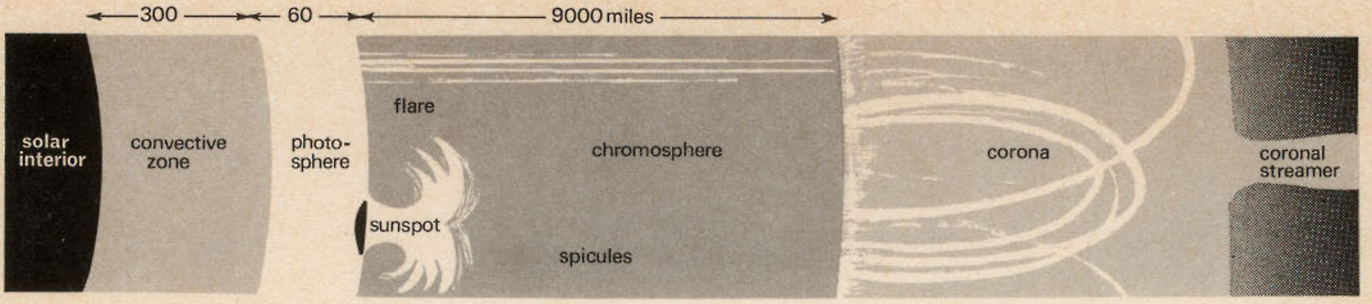
In a layer about 5000 km thick between the 6000 K photosphere and the corona drastic changes occur: the electron temperature increases by a factor of 300, density falls through eight orders of magnitude, radiative and thermodynamic equilibrium break down, and the solar plasma falls under the control of the Sun's magnetic fields. This region is the seat of solar flares, spicules and prominences, and probably the principal locus of the mechanical force that supports the corona and creates the solar wind. The layer is dynamic and spatially complex and is easily observed from the ground only in its lower layers, at heights corresponding to the levels of origin of the centres of strong Fraunhofer lines: chiefly Balmer α of hydrogen (Hα), and the H and K lines of singly-ionised calcium. Above this level a rapid increase in temperature and ionisation shifts the principal line emission to shorter wavelengths, beyond the reach of observation from the Earth.

The solar atmosphere above the low chromosphere is composed of gaseous metals in ever-increasing states of high ionisation whose emission lines fall in the ultraviolet. By observing the disc of the Sun with a spectroheliograph or other monochromator in these narrow wavelengths, one "sees" specific layers of the chromosphere, transition region, and low corona. This ability literally adds a new dimension to the already complex picture of the low chromosphere more commonly seen in Hα and Ca H and K. The ultraviolet emission lines are superimposed on a fairly weak continuum background and hence are readily observed over the disc of the Sun. Unlike the sparse and infrequent observations of the chromosphere and corona at eclipse, which momentarily reveal the edge-on view, the ultraviolet spectroheliograms can portray an entire hemisphere and thus reveal detailed and unambiguous correlations with the lower Hα chromosphere and other key observables such as photospheric magnetic fields.

NEW VIEW OF THE CHROMOSPHERE

Previous theoretical sketches of the vertical appearance of chromospheric structures are now clarified by the detailed observations from the several ultraviolet experiments on ATM. The vertical extent of the chromospheric network appears in detail for the first time. Spicules, which outline the giant circulation cells of the network, are observed to extend from their commonly-observed location in the low, Hα chromosphere through the transition region, where they appear with maximum contrast in ambient temperatures of 100 000 to 200 000 K. At temperatures of a million K in the low corona, spicules, and presumably the network, fuzz out and disappear, suggesting that magnetic field lines, which delineate the network boundary, diverge in the corona. Of immense importance to the understanding of the solar atmosphere are ATM's continuous observations of the vertical extent of active regions and of flares, which are recorded with high spatial detail from the chromosphere to the low corona. Details of eruptive events at the limb were seen for the first time in the Lyman α line of ionised helium, 304 angstroms. The many high-resolution spectra taken of a variety of disc features with the US Naval Research Laboratory's ultraviolet spectrograph make possible the analysis of spectral line profiles of these regions — employing the most powerful tool of analytical astrophysics.

In like fashion different heights in the low and intermediate corona can be observed by isolating specific wavelength bands in the X-ray spectrum of the Sun, where peak continuum emission shifts in wavelength with temperature. Harder X-rays originate generally lower in the corona. The spectral bands available to the two ATM X-ray telescopes were chosen to bracket the low and intermediate corona and to portray all forms of coronal density structures — from coronal holes to flare enhancements and condensations. The ATM X-ray pictures show all of these in exquisite detail — again over the entire hemisphere — and in some cases extend to a height of half a solar radius above the limb (1·5 $R_\odot$), where the X-ray observations overlap with the lower bound of the ATM coronagraph coverage.



The main features of the Sun's atmosphere

First results from the ATM X-ray observations seem to destroy all vestiges of the common concept of a homogeneous background corona which had served as a basis for much of modern coronal physics. In clear, 2-arc second detail the X-ray pictures reveal that the corona is composed almost entirely of closed loop structures which fit very well, on first examination, magnetic field lines calculated from observed photospheric fields. Short- and long-term magnetic restructuring of coronal field lines is observed in both X-ray and white light coronagraph pictures. Previously-seen coronal bright points which apparently are the X-ray manifestation of incipient active regions, turn up over the entire disc, including near the poles, outside the conventional latitude zones of visibly-observed sunspots. Low-density coronal regions called coronal holes, now thought to be the principal loci of terrestrially important disturbances in the solar wind, are extremely well displayed, for the first time, by the ATM X-ray pictures (Figure 1).

In the outer corona, densities decrease outward from about 10^7 to 10^4 particles per cu.cm at a roughly constant temperature of 1 to 2 million K. Atomic emissions here are weak and the region is seen in best detail by observing the photospheric light which is scattered by the free electrons making up the corona. Since the maximum of photospheric emission falls at about 6000 angstroms, this observation can be made in the visible, and for this purpose the ATM carried a white-light coronagraph. Details of the lowest corona are seen by conventional coronagraphs at mountain sites on best days, but patrol instruments which reach above about 1·5 $R_\odot$ have been characterised by relatively coarse angular resolution and slow picture rates, because of the sky background glare. Thus our knowledge of the detailed structure of the outer corona has come almost completely from total eclipses, where nature allows, on the average, a view of only a few minutes per year. The ATM coronagraph — of optimum optical design and situated above terrestrial scatter — promised a revolutionary chance to observe the corona with fine detail on a synoptic basis. As with the other ATM instruments, its results exceeded expectations, yielding tens of thousands of eclipse-quality photographs of the corona from the edge of its occulting disc (1·5 $R_\odot$) to about 6 $R_\odot$.

When the first Skylab crew splashed into the Pacific after the 28-day SL2 mission, they brought with them exposed coronagraph film which represented more hours of observation of the outer white light corona than had been acquired in the millenia of man's observation of this elusive phenomenon at natural eclipse. More important, unlike the snapshot album from eclipse records, the ATM time coverage was continuous and truly synoptic. In it were the surprises that one anticipates in the first good look at previously unseen phenomena. On the film from 10 June appeared a great transient blob the size of the Sun itself which moved outward through the corona at about 400 km/s, the first time that such an event had been observed in detail in the outer corona. When the coronagraph was turned off at the end of the last SL4 mission, more than 40 of these events had been recorded and their correlations with eruptive prominences and other activity established. Other more continuous change was noted in the hour-to-hour coverage.

A COOPERATIVE SUN

The Sun itself seemed to favour ATM, as we see in Figure 2, where we show for the 257 days of Skylab the variation of daily relative sunspot number — a common measure of solar activity on the visible hemisphere. The three periods during which Skylab was manned are shaded. An inset shows the annual means of sunspot number for the past 40 years and indicates the well-known 11-year periodicity. The ATM was originally envisioned for operation during the 1969–1970 solar maximum when the chances of flares and other dynamic events were greatest. As the programme slipped in time, many were concerned about the returns that could be expected from a mission so near the minimum of the 11-year cycle. As we see in the daily counts, the Sun during Skylab was far from quiet. In early September, during the second manned mission (SL3), activity reached a level characteristic of

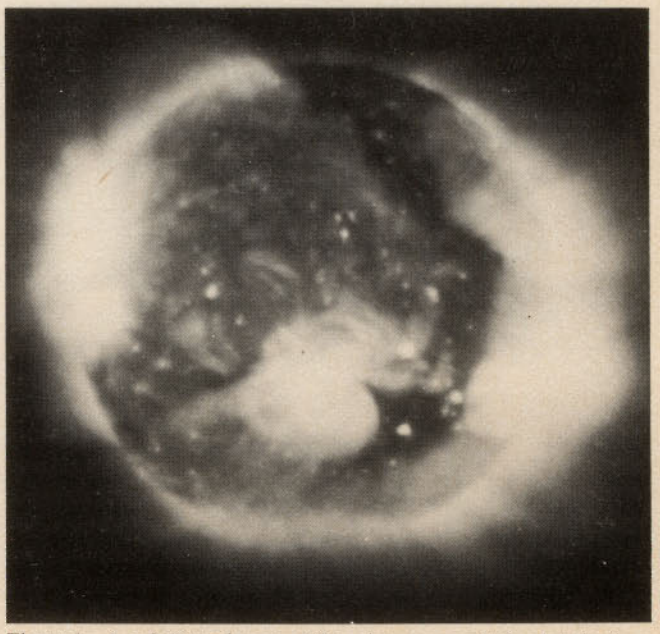


Figure 1 A soft X-ray image of the solar corona obtained at the time of the 30 June 1973 solar eclipse by the AS and E telescope on Skylab. Bandpass is approximately 3·5 to 54 angstroms. Bright points in the corona are seen over the entire disc. The quiet corona appears as diffuse loops on the disc and above the solar limb. The dark lane starting at the top is a coronal hole

the maximum in the solar cycle. During the early September peak several major flare events were observed by the combined ATM battery. Others were observed in the manned SL2 and SL4 missions, some with complete coverage of the crucial starting phase, as were numerous eruptive prominences and other dynamic events. In early August, early November, and on several instances during SL4, the visible hemisphere of the Sun showed no sunspots for periods of two to six days, providing valuable opportunities to obtain detailed and coordinated measurements of the truly quiet Sun. Particularly during SL4, the Sun exhibited an active and a quiet hemisphere, divided in longitude, which appears in the figure as a cyclic activity with period equal to the 27-day rotational period of the Sun.

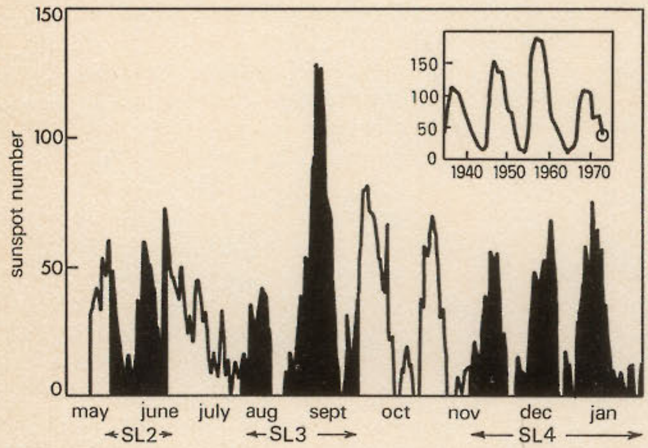


Figure 2 Daily relative sunspot number for the duration of Skylab 14 May 1973 through 8 February 1974. Periods of the three manned Skylab missions (SL2, SL3 and SL4, respectively of 28, 59, and 84 days) are shaded. Inset shows the annual mean of the daily sunspot numbers for the period 1935 through 1973. The small circle in the inset indicates the portion shown in expanded form in the larger graph

Why was the ATM so successful? Most of us outside the programme did not expect it to achieve quite as much as it did. None of the six ATM experiments was new in space. Each had been there before, albeit in more rudimentary form, on earlier spacecraft of NASA's Orbiting Solar Observatory series. The Sun has been studied throughout the ultraviolet and X-ray region by rockets and satellites for more than a decade. A white light coronagraph was operated in Earth orbit on OSO-7 launched in 1971, and in rockets and balloons long before that. But the ATM offered a number of differences which proved to be truly significant:

1. The instruments were large-scale and highly sophisticated. Because of Skylab's size, instrument dimensions and power allowances were almost unrestricted, as measured by the standards of previous solar space experiments. The six principal instruments were generally three metres long and their combined weight was nearly 1000 kg. Yet they were stabilised and pointed to a tolerance that at times was better than 1 arc second — which probably equals what could have been done with the same package on an observatory pier on Earth. As a result, each instrument brought significant advances in one or all of the three critical parameters of solar observation: *spatial* resolution (clarity of detectable detail); *spectral* resolution (height discrimination in the solar atmosphere); and *temporal* resolution (ability to detect changes with time). In some cases the improvements over past efforts were measured in orders of magnitude.

2. Data storage was not a severe restraint. The Skylab bulk and operational support made available to the ATM not only a generous telemetry capability for primary and auxiliary data transmission, but a unique possibility to utilise the great information storage capabilities of ordinary photographic film. Six of seven experiments used film, and preloaded cameras were replaced in orbit as reel upon reel was exposed. In all, hundreds of thousands of frames were secured and successfully returned to the experimenters for processing in their own facilities. For the total manned and unmanned ATM operation, the average is about 600 solar photographs per day, each of generally superb quality and each capable of recording about 10 bits of information.

3. The instruments were used with record efficiency — a quantity not always measured in astronomy. Man had never had before him the controls of so many different astronomical instruments as were on the ATM control console (Figure 3). Nor had he ever seen the Sun simultaneously in the selection of real-time displays that were available to the Skylab astronaut. At the turn of a switch he could display the Sun on either of two television monitors in Hα, white light, broad-band XUV (170 to 550 angstroms) or view the outer white-light corona. He could "zoom in" for better looks or for precise pointing. Other real-time presentations were available in different X-ray bands, as were total-flux monitors in X-rays and in solar radio noise of 3 cm wavelength. These capabilities proved highly effective in opportunistic and directed target selection, and instrument coordination. Success in observing the important rise phase of a number of solar flares was entirely due to alert use of these on-board capabilities by the astronauts. Finally, three of the ATM experiments could operate, in more limited modes, during unmanned periods, as during times of astronaut sleep or during the weeks when Skylab was crewless.

4. The six instruments of ATM were operated much of the time *in concert*, in joint observing programmes which had been composed and rehearsed in the years of preparation before the 14 May SL1 launch. This made possible the coordinated observation of specific areas of the quiet and active Sun and of many targets of opportunity, such as solar flares. The simultaneous observation of dynamic solar events at various heights in the chromosphere and corona had been a long-held hope of solar physics. It could be the key to understanding these events and their prediction. From the ATM simultaneous observations of the quiet Sun we can expect real improvements in the presently sketchy models of the high chromosphere and transition region.

5. Conventional solar physics gave the mission extensive ground support. The astronauts and instruments aboard Skylab were but the peak of a pyramidal support structure at Houston which rested on a broad base of outside support. This included the dedication of a world-wide net of solar activity stations maintained by the US National Oceanic and Atmospheric Administration; and a heavy commitment to concurrent, coordinated observing programmes by many of the world's solar observatories. At the Johnson Space Center in Houston where Skylab was controlled, experiment control consoles were staffed around the clock for the full duration of the mission by a tightly-organised structure of solar physicists and engineers on the experiment teams. Each day in a strategy meeting experiment representatives decided

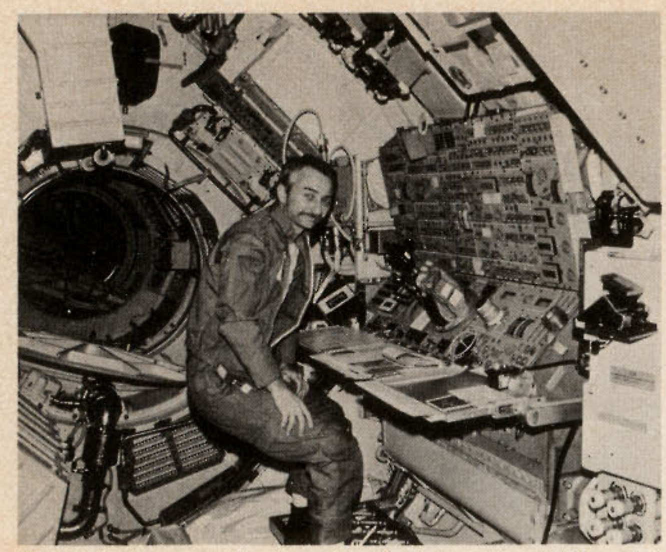


Figure 3 Astronaut Dr Owen K. Garriott at the ATM control console during the Skylab 3 mission. Before him are the controls and monitors of the principal solar experiments

the minute-by-minute schedules of each solar instrument, based on solar activity predictions from the ground and from Skylab itself. In a solar period which was surprisingly active and varied (Figure 2), nearly every event on or near the Sun was effectively observed, including numerous flares and eruptive events, two solar eclipses, a transit of Mercury, and the perihelion passage of Comet Kohoutek.

6. The astronauts saved the solar mission on repeated occasions and without much doubt were the difference between success and failure for the terribly complex system which was ATM. In the original mission concept, crew members were to provide pointing, target selection, and some control, and to retrieve and replace cameras during extra-vehicular activity (EVA). Their first spectacular role in patching the Skylab together after a nearly fatal launch mishap is well known. Less heralded are a sequence of efforts which salvaged the solar experiments again and again and kept them running at full speed up to the planned end of the mission. These included — all by EVA — pinning open experiment doors which had failed in closed position; replacing a jammed camera; removing threadlike objects which collected on two occasions on the coronagraph occulting disk; and a rather intricate screwdriver repair of a shutter mechanism and jammed filter wheel. Inside Skylab, at the ATM console, a defective cathode ray tube was replaced and a number of modifications were made to various control functions, following specific failures or recommended improvements. The opinion of the solar principal investigators is, needless to say, wholly enthusiastic in endorsing the role of man for sophisticated missions such as Skylab AMT. At the end of this particular round of the continuing bout between men and machines in space, the man is the winner by the unanimous decision of the judges present.

It is much too early to assess the full impact of ATM on solar physics. It was solar physics' most expensive experiment, accounting for possibly 10 per cent of the total Skylab cost of $2·6 billion. But a part of this funded conventional, supporting, solar research during the period. And the results of ATM will be shared in collaborative guest-investigator programmes involving hundreds of scientists in many countries. If we may judge its cost-effectiveness in terms of scientific yield per dollar spent in space, ATM now appears to have been a rather good investment.

MERCURY ☿

JOHN GUEST

Mercury, the last of the terrestrial planets to be investigated by spacecraft was encountered by the United States Mariner 10 spacecraft on 29 March 1974.

Mariner 10 was launched from Cape Kennedy in the early morning of 3 November 1973 by Atlas/Centaur; the science instruments were turned on as early as six hours after launch, the TV cameras taking pictures of both Earth and the Moon. These early pictures allowed the instruments to be calibrated for future comparison with Venus and Mercury. After this Earth/Moon calibration sequence the craft sped on towards its goals of Venus and Mercury to become the first spacecraft to take pictures of all the terrestrial planets except Mars. The spacecraft was assisted on its way to Mercury by Venus's gravity which pulled Mariner round on a trajectory towards the inner part of the solar system. This was the first double flyby in the history of space flight.

Picture taking at Mercury began on 23 March 1974 after five months of eager anticipation. These first pictures (Figure 1) had a resolution on the planet's surface of about 130 km, better than any Earth-based telescopic observations which have resolutions of around 300 km. At that distance the planet appeared almost featureless, but on successive days towards encounter bright markings became visible. One particularly bright spot was observed initially near the limb but moved closer to the centre as Mercury rotated. By 25 March, four days before encounter and at a distance of 3·5 million km, the surface of Mercury had the appearance of rough orange peel near the terminator. At this point the resolution was about 80 km. The following day, with a resolution of about 60 km, craters were clearly visible. This period of far encounter, as day by day the spacecraft got closer to Mercury, was both exciting and tantalising for those who were watching the pictures being returned. Just before encounter it was clear that Mercury was a cratered planet looking remarkably like the Moon. During encounter, picture taking was almost continuous with the spacecraft rushing towards and by the planet at a speed of about 11 km/s. The pictures were taken in the form of a series of mosaics of the whole of the visible disc, each mosaic being of higher resolution as the spacecraft got closer (Figure 2). A similar sequence of mosaics was taken looking back at the other face of the planet as Mariner 10 receded from Mercury (Figure 3), and continued on its way into orbit around the Sun. The

highest resolution pictures taken just before and just after near encounter did not form a complete mosaic but were spaced over the surface; these pictures had resolutions as good as 100 metres.

On 21 September 1974 Mariner 10 re-encountered Mercury having made a complete orbit of the Sun. This time it passed on the planet's bright side, photographing new areas and giving better coverage of the southern hemisphere. This was the first time a spacecraft had re-encountered its target planet.

Mercury, the innermost planet of the solar system, orbits the Sun at 0·39 of an astronomical unit (an astronomical unit is the distance of Earth from the Sun). Its radius is 2439 km making it about one-third the Earth's diameter. The Moon is about a quarter the Earth's diameter, whereas Mars is about half. With a density of 5·4 g/cu.cm, comparable with that of the Earth, and yet a smaller radius, Mercury must have a large metallic core that may make up 70 to 80 per cent of its radius.

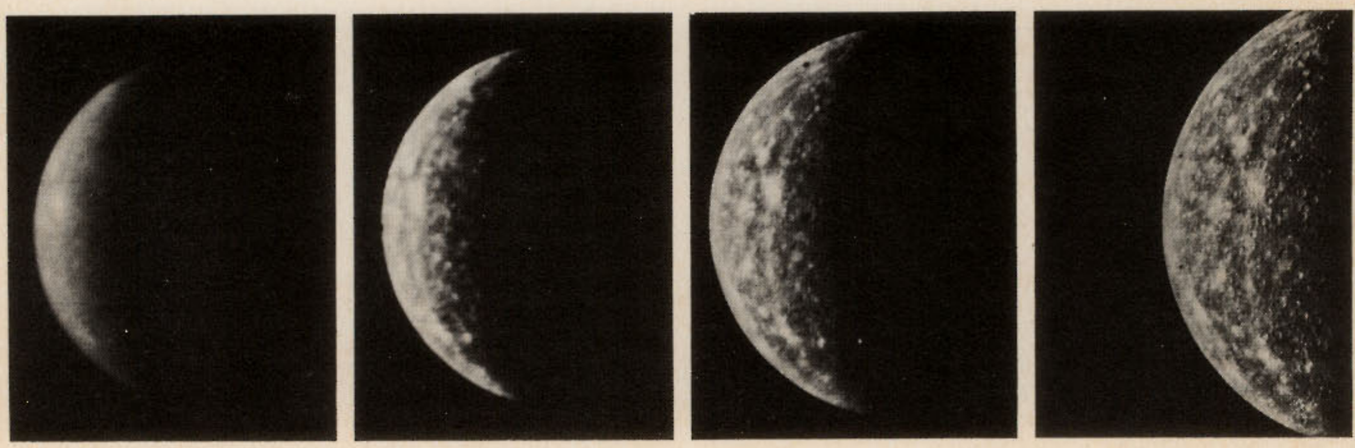
Before Mariner 10 Earth-based astronomy had shown that Mercury has faint light and dark markings: but a maximum resolution of about 300 km from our terrestrial vantage point revealed no details. Studies of the optical properties showed that the surface characteristics are similar to those of the Moon implying that Mercury has a regolith of fragmental material and that its surface has been bombarded by meteoritic material. However, no one knew *how* cratered the surface of Mercury would be. Its great distance from the asteroid belt by comparison with Mars or the Moon had suggested to some workers that Mercury would be much less cratered than either of these two bodies.

Mariner 10 showed in a dramatic way that Mercury was cratered in the same way as the Moon and also had two broad types of terrain: one was densely cratered with large craters to resemble the highlands of the Moon; while the other terrain type consisted of relatively poorly cratered plains analogous to the lunar maria. The Earth-based telescopic observations indicated that one hemisphere of the planet showed more contrasting albedo (brightness) markings than the other hemisphere. Mariner 10 viewed a part of both these hemispheres and it may be significant that, while the incoming pictures showed Mercury to be densely cratered, the outgoing view showed extensive tracts of plains materials as well as densely cratered terrain: the outgoing view corresponded to the hemisphere with more albedo markings.

CRATERS AND BASINS

Craters cover the surface of Mercury and range in diameter from less than 100 m up to the largest basin which is 1300 km across. The morphology of craters is similar to that of their lunar counterparts and depends on the size and age of the individual crater. Criteria well defined for the Moon indicate that they are impact craters. The smallest craters up to about 10 km are, when fresh, bowl-shaped with well developed sharp rims, ejecta deposits, and fields of secondary craters (that is craters formed by missiles ejected from the primary crater during its excavation). Some have small central peaks and the freshest ones have bright ray systems surrounding them. Older craters in this size range have subdued rims surrounding barely discernible depressions. The larger craters also have well defined ejecta surrounding them but the inner walls of the craters are terraced and the floors are generally flat. Central peaks or clusters of central peak material are prominent. At 200 km, and above, in diameter the craters are more like lunar basins with a multi-ringed form (Figure 4). There is a normal outer rim unit and an inner mountain ring on the floor of the crater. These multi-ringed craters may also have a central peak.

One striking difference between these fresh craters and those on the Moon is that the ejecta blankets are apparently less extensive than those around their lunar counterparts, and the fields of secondary craters are correspondingly closer to the crater rim. This characteristic, together with an apparent shallowness of Mercurian craters compared with those of the Moon and the well developed nature of central peaks and ring structures, may well be a result of the much higher surface gravity of Mercury compared with that of the Moon. Surface gravity at Mercury is comparable to that on Mars and is twice that of the Moon. Thus differences in impact cratering-style are to be expected on Mercury, the ballistic range of ejecta being reduced, and a greater



a b c d

Figure 1 Far encounter pictures of Mercury from Mariner 10.

a Taken on 24 March at range of 4 320 000 km with a resolution of about 100 km

b Taken on 25 March at 3 500 000 km with 80 km resolution

c Taken on 27 March at 1 840 000 km with 41 km resolution: craters are seen at termination

d Taken on 28 March at 952 600 km with 20 km resolution

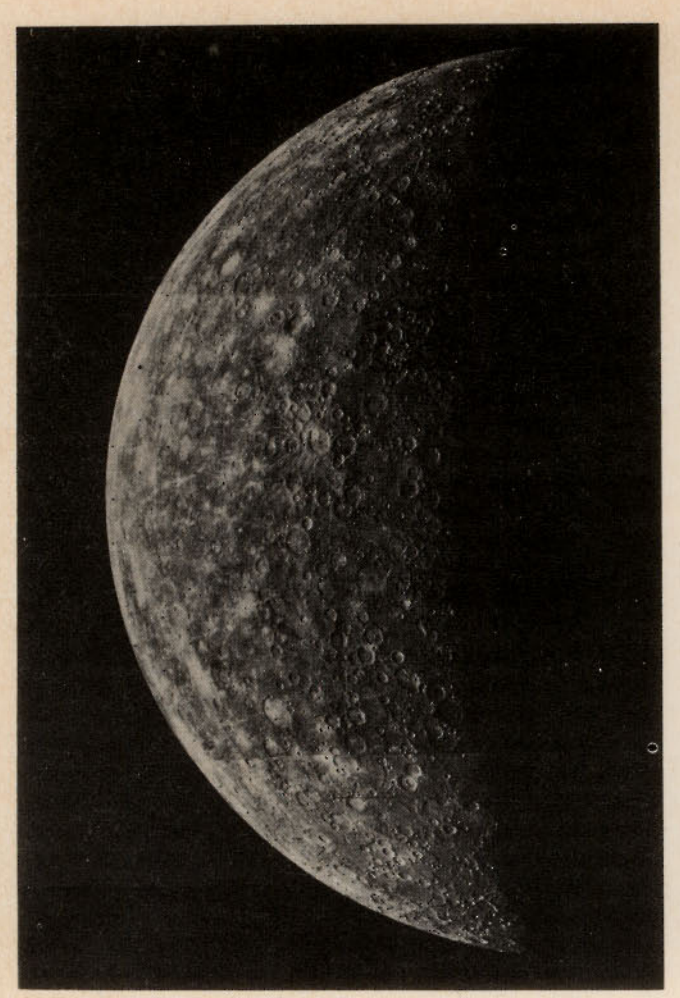


Figure 2 A mosaic of higher resolution pictures to show the incoming face of Mercury. This face is densely cratered and resembles the lunar highlands. Just above the middle of the planet as seen here there is a bright rayed crater (preliminary name: Kuiper) that was seen as a bright spot in preceding pictures. It is 40 km in diameter

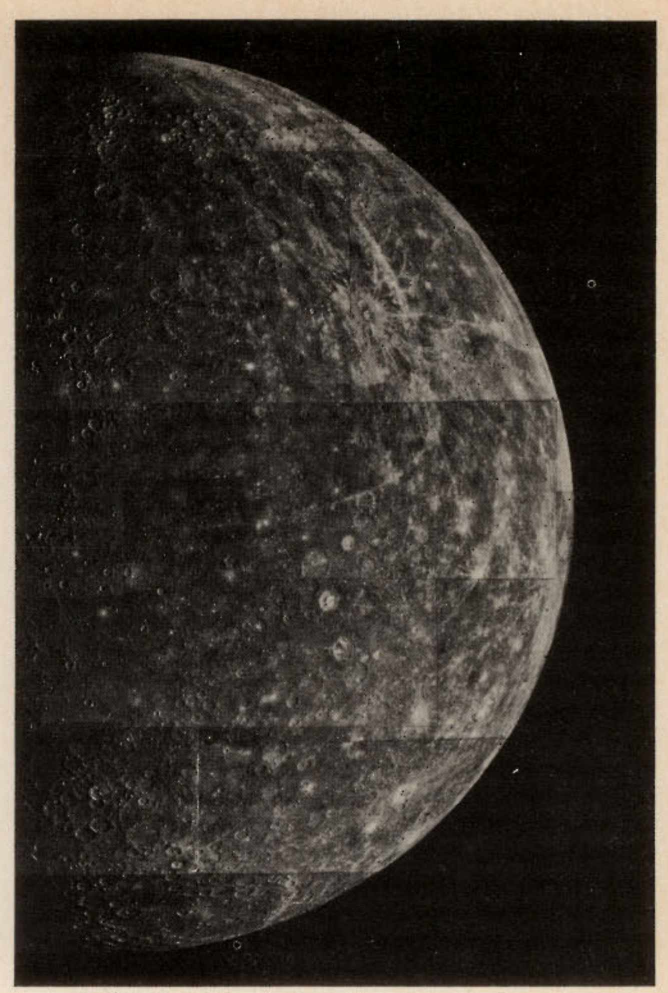


Figure 3 The outgoing view of Mercury made up as a mosaic. The 1300 km Caloris basin in clearly seen near the terminator. Round Caloris and near the North Pole are vast areas of plains. Bright rayed craters are seen near the limb

degree of post-cratering collapse through slumping of the rim being expected.

The highlands of Mercury have a similar appearance to that of the lunar highlands with close-packed large basins and craters with superposed smaller craters the densities of which vary depending on the age of the underlying crater. Preliminary analyses also suggest that there is a higher proportion of secondary impact craters covering the terrain than is seen on the Moon. This presents something of a problem because, unless one crater can be seen to overlap another crater directly, age relations between craters are determined by their relative degree of degradation. The degradation is the result of continued cratering by smaller particles that break down the original structure until eventually it disappears. Although normally this erosion is considered to be produced by primary impacts hitting the surface, secondary impacts can also accomplish the same thing. Many large craters appear to be covered by secondary craters and these, rather than primary impacts, might well have caused their destruction. Whereas primary impact caused by steady bombardment of meteoroidal objects is a continuous, cumulative and planet-wide process, secondary cratering is a local phenomenon. Thus it would appear that in some cases the degree of degradation of an older crater depends on its closeness to another large fresh crater. At first sight it is difficult in some cases to make age correlations over a wide area based on the degree of denudation of craters.

The Caloris Basin (Figure 5) is unique on the observed surface of Mercury. This basin, some 1300 km in diameter, is surrounded by a ring of mountains rising to about 2 km above the surrounding surface. Extending out from the mountains is a surface characterised by strings of hills separated by grooves that are sub-radial to the Caloris Basin. The Basin has many features in common with the Imbrium Basin on the Moon and is considered to have formed in the same way by the impact into Mercury's surface of a large body of asteroidal size. The floor of the basin is covered by plains material that has developed on its surface a striking pattern of ridges and "cracks" that are both concentric and radial to the Caloris structure. Although ridges occur in plains materials elsewhere outside Caloris, the fracture pattern does not. This pattern implies post-emplacement movement of the plains material in response to stresses developed within the basin after its formation. However, the exact nature of these stresses is at present undetermined.

THE PLAINS

Plains materials are distributed widely on the outgoing view of Mercury (Figures 6 and 7) and form patches especially within craters in the ingoing views. A particularly well developed expanse of plains materials is found surrounding the Caloris Basin; another vast expanse is within a large circular structure near the North Pole. Preliminary studies of these plains

materials have lead members of the Mariner 10 TV team to conclude that they are vast tracts of lavas. This argument is based largely on the distribution of the plains, which shows they are not associated solely with large craters in which case they could represent ejecta rather than lava fields.

There is no evidence of individual volcanic vents as seen in some places on the lunar maria. However, even on the Moon, vents in the form of domes or small cones are rare and are only seen at low lighting conditions; the Mariner 10 pictures of Mercury show only a very small proportion of the visible planet under such low lighting. Most of the materials forming the lunar maria are considered to have been formed by flood basalt volcanism — that is, eruptions of large volumes of very fluid lava that spread for several hundred kilometres from the source. It is a characteristic of such eruptions that vents are difficult to recognise after the eruption because the lava, being highly fluid, does not lead to explosive activity which would build cones over the vents. Thus no lines of fissure cones or other features are formed. One likely explanation of the Mercurian plains is that they were formed in a similar manner. If this is so it would appear that after the majority of the large craters were formed volcanism became the dominant surface process on Mercury. However, some volcanism was also probably taking place during the period when the large craters were being formed.

In most areas where the plains materials occur they have been modified by the formation of long ridge features that are similar to the wrinkle or mare ridges of the Moon. The origin of these features is debatable for the Moon; generally they are considered to be the result of post-emplacement movement of the surface of the maria to produce either ridges of up-arched surface strata, or a thrust fault system resulting from sliding of one slab of lava over another. The evidence also suggests for the Moon that some extrusion has taken place along these ridges in some areas. There is also evidence from the Moon that these ridges often reflect the topography underlying the mare materials so that where craters have been entirely buried their position may be marked by a mare ridge ring. The same may also be true for Mercury where complex patterns of ridges near the edge of the plains materials form roughly circular or polygonal patterns. Other evidence that in some areas, especially around Caloris, the plains materials are relatively thin is given by the presence of small hills of the underlying terrain poking up through the plains.

The presence of plains material concentrated in the region of the Caloris Basin tends to imply that these plains are associated with the Basin. It is possible that the strong deformation and fracturing of the Mercurian crust in the region of this gigantic impact provided the channels through which magma, generated at a depth of perhaps several hundred kilometres, could rise to the surface. However, there still remains the possibility that the plains are not volcanic but ejecta associated with Caloris and other big basins.

Not only are the surface processes on Mercury similar to those of the Moon but also the surface history appears to have been remarkably similar. It seems that like the Moon, Mercury went through an early phase of intense bombardment producing large craters and basins. This may well have been accompanied by volcanism. After this phase meteoritic impacts became less frequent and, assuming the plains to be lavas, volcanism became the dominant surface process accompanied by sporadic impacts of large bodies and

Figure 4 Two large craters. The northern one is a 200 km multi-ringed basin with chains of secondary craters surrounding it (especially on the west side). To the south is a smaller crater with well developed central peak. Plains are clearly seen to the far west.

Figure 5 A mosaic of the Caloris Basin. The rim of mountains surrounding the basin is clearly seen. Inside, the plains are characterised by cracks and ridges while, outside, plains material has only ridges. To the north east can be seen part of the lineated terrain representing the Caloris ejecta

Figure 6 A close up of the plains on Mercury's outgoing view

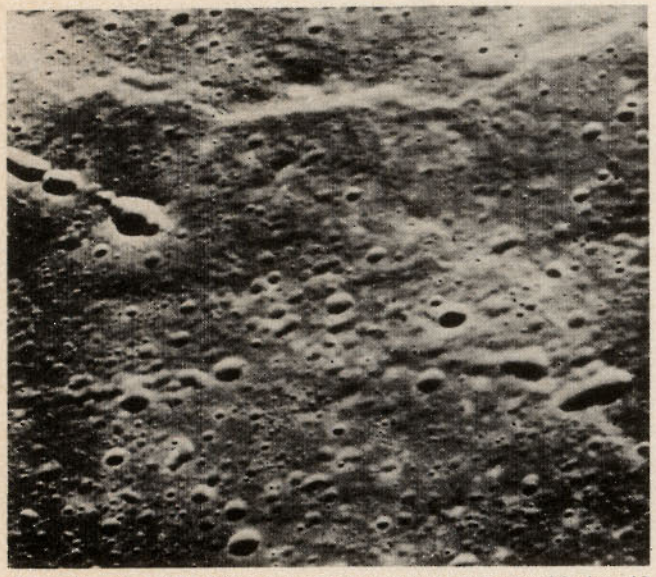


Figure 7 One of the highest resolution pictures taken by Mariner 10 showing an area of about 50 × 40 km. It shows the level surface of the plains. The surface is peppered with small craters: and scarps and ridges reminiscent of the lunar maria

more common impacts of smaller ones. This is exactly the same history as the Moon; but it is only possible to show that the *sequence* of events was the same. Without obtaining samples of Mercury's surface the absolute chronology of this sequence cannot be determined.

An important conclusion from studies of Mars, the Moon, and Mercury is that all these bodies had an early phase of intense bombardment and the implication is that the formation of terrestrial planets is normally followed by such a phase. Of course on Earth evidence of bombardment has been removed, the oldest rocks known on Earth being about 3500 million years old. On the Moon this phase of intense bombardment took place before 4000 million years ago. This result is not surprising as one might expect the final phase of terrestrial planet formation to be the sweeping up of débris within the orbit of the planet until this débris is exhausted.

Rather more surprising is the apparent similarity in internal activity on Mercury with a phase of extensive, apparently basaltic, volcanism again occurring probably early in the planet's history. This result was not predictable before Mariner 10 because Mercury had already been interpreted as being more Earth-like than the Moon in having a large metallic core. The difference in internal constitution might have been expected to produce a different thermal history in the Mercurian crust from that of the Moon.

As far as the internal constitution of Mercury is concerned, the present results lead to the conclusion that Mercury became chemically differentiated very early in its history before the period of intense bombardment. If the period of intense bombardment came close after the formation of the planet by accretion then the planetary differentiation may be considered to have taken place during the later stages of accretion.

UNEXPECTED MAGNETISM

One exciting result of the Mariner 10 mission is the detection of a magnetic field associated with Mercury. Planetary scientists had in fact predicted its absence on the grounds that the planet's rotation was too slow and its radius too small. The observed field has been interpreted by Mariner 10 scientists as resulting from an intrinsic magnetic field rather than being one induced on the planet by the solar wind. Assuming the magnetic field to be intrinsic, there are two possibilities: one is that Mercury, like the Earth, is behaving as a dynamo generating its magnetic field; or alternatively that we are now seeing a fossil magnetic field that was produced by the planet much earlier in its history. If the deduced history of Mercury is correct then much of its present surface developed very early and has had little modification since. This being so it is unlikely that any strong forces have originated from within the planet or these would certainly have modified the present surface. It thus seems unlikely that a dynamo mechanism has been working within Mercury throughout all its history and the fossil magnetic field is the more likely possibility. There is evidence that Mercury's crust was mobile in its early history as evidenced by the presence of long scarp features running across the older, and in some cases younger, surfaces. These scarp features are difficult to interpret but it is most likely that they are large thrust fault scarps. Such features might be expected on the surface of a planet that at one time underwent internal movements.

Clearly the Mariner 10 mission was a remarkable success and is a credit to all the scientists and engineers who were responsible for it. It must be remembered, however, that we have seen less than half of the total surface of Mercury and experience shows that drawing planet-wide conclusions without seeing the whole planet can be dangerous. It is remarkable that all the terrestrial planets appear to have two different hemispheres. A view of Earth would show one hemisphere largely water covered, and the other hemisphere largely land; of the Moon one half would be seen as highlands and maria, the other just cratered highlands; and Mars has a southern cratered hemisphere and a northern hemisphere consisting of plains materials and volcanoes. As we observed earlier, telescopic observations showing that one half of Mercury is different from the other were at least in part confirmed by the vast tracts of plains on one of the portions observed by Mariner 10 but not on the other. We must await further exploration of Mercury before many of the questions concerning this planet will be answered.

(The results reported in this article are the outcome of teamwork. The TV imaging team is still working on the Mariner 10 mission.)

VENUS

GARRY HUNT

Venus, our nearest planetary neighbour and the brightest planet in the sky, has fascinated and frustrated astronomers for centuries. Its mass and radius are similar in magnitude to those of the Earth, suggesting that Venus is our planetary sister. But there the similarity ceases.

The Venus atmosphere is huge, more than 100 times more massive than the Earth's and composed primarily of carbon dioxide. Traces of hydrochloric and hydrofluoric acids have been detected but there is apparently very little water in the Venus atmosphere. The surface temperature of the planet is approximately 736 K — more than three times the highest temperature (absolute) presently measured on the surface of the Earth. It also appears that the surface temperature of Venus does not vary greatly with latitude or solar phase angle since the coldest regions, which lie on the equator near the sunrise terminator, may be within 10 to 20 K of the warmest regions. But little is known of the properties of surface and lower atmosphere since only microwave radiation and space probes can penetrate far enough to yield any information.

For, throughout the centuries, numerous photographs taken of Venus have produced only one frustrating result; the planet is covered by a uniform unbroken layer of yellowish cloud whose top may be up to 100 km above the ground and which reflects 79 per cent of the total sunlight it receives. This is in complete contrast to the Earth, which has on average only 50 per cent cloud cover and which reflects approximately 31 per cent of the incident sunlight. But ultraviolet photographs produced a totally unexpected result. Quasi-permanent faint markings, in the form of a dark horizontal Y or C, suggested an equatorial motion with a four-day period which would require winds of 100 m/s at these cloud top levels. That is an incredibly rapid rotation when compared with the planetary rotation period of only 243 days. Both the planetary and ultraviolet rotation periods are in the opposite sense to the Earth. The cause and origin of these features and their relationship to the general circulation of the atmosphere has stimulated numerous explanations from the limited amount of observational material. The high-resolution pictures taken from the Mariner 10 fly-by have now added a further complicating dimension to this intriguing problem. Mariner 10, flew past Venus at 1701 GMT on 5 February 1974 at a distance of only 5785 km.

The density of Venus is 5·26 g per cu.cm and similar to that of the Earth suggesting it may have an iron core. The rotation of the planet is, however, too slow for a planetary magnetic field to be induced by a dynamo action. Indeed Mariner 10's magnetometer experiment confirmed that the magnetic field of Venus must be less than 0·05 per cent of the Earth's field, which is 0·5 gauss. For more than six days preceding the Venus encounter the interplanetary magnetic field appeared distorted in a manner suggesting that there is a magnetic tail extending behind Venus from the Sun, similar to a comet's tail. Shortly before the radio occultation the magnetic field doubled in magnitude from approximately 10 to 20 gammas (1 gamma $= 10^{-5}$ gauss). This may be interpreted as a crossing of a bow shockwave. The way in which the ionosphere deflects the solar wind plasma is, however, of a new type, quite unlike those associated with the Earth, Jupiter, Moon or Mars, and will therefore require further study by an orbiting spacecraft.

Mariner 10 carried experiments with two radio frequencies to probe the Venusian ionosphere and atmosphere at occultation; S band at 2295 MHz and X band at 8415 MHz. The results show that the Venusian ionosphere is considerably less structured than the corresponding region on Jupiter. The nightside ionosphere consists of two layers having a peak density of 10^{-4} electrons per cu.cm at altitudes of 140 and 120 km. The dayside ionosphere has a peak of 3×10^{5} electrons per cu.cm at an altitude of 145 km.

The Earth's atmosphere evolved slowly over geological time though the out-gassing at the surface from crystal rocks in hot springs and volcanoes. Generally, the main volcanic gases were water and carbon dioxide with a small amount of nitrogen. The nitrogen remained in the atmosphere. The carbon dioxide ultimately combined to form the solid carbonates, or was used by plants in photosynthesis with a resulting release of oxygen into the atmosphere. As the atmosphere built up through out-gassing the temperature rose through the "greenhouse effect", although it always remained sufficiently cool for the water to collect in the form of oceans.

But how did Venus obtain its atmosphere? There is little evidence to support the claim that it was produced by out-gassing. The position of Venus at 6 to 10 million km nearer to the Sun than the Earth would have made its exposed surface too hot for any water vapour to condense to form oceans. Consequently, the huge atmosphere would have built up through a greenhouse process enabling the carbon dioxide to accumulate in the atmosphere, while the water became lost in the upper troposphere through reactions with other minor constituents to form the observed sulphuric acid droplet clouds. The limited amount of water vapour which reached the upper atmosphere would then be efficiently dissociated by the action of ultraviolet sunlight while the remaining hydrogen could have escaped into interplanetary space. But the ultraviolet spectrometer on Mariner 10 detected hydrogen suggesting that at heights between 1000 and 500 km the hydrogen has increased by a factor of two. What then is the origin of this hydrogen? One theory is that it came from a chance impact with a large cometary nucleus. Cometary nuclei are generally rich in deuterium so that, if a comet was the original source, Venus should be in this enriched state. However, the Mariner 10 ultraviolet spectrometer has found little evidence for deuterium in the Venus atmosphere.

The solar wind is a more likely source of the Venusian hydrogen. Since Venus lacks extensive Van Allen belts of trapped radiation to protect it from the interplanetary environment streams of solar protons can lose their charge to the constituents of the Venus upper atmosphere, becoming electrically neutral and subsequently impacting the planet. The lack of deuterium is consistent with this hypothesis. The Sun consumes deuterium in nuclear reactions which occur in its interior so that much of its original supply of this heavy isotope of

hydrogen has been depleted over 5 billion years and the concentration of deuterium in the solar wind at the present time will therefore be immeasurably small.

The Mariner 10 hydrogen observations indicate an exospheric temperature of 400 K while the hydrogen escape rate from Venus is approximately 10^4 atoms per sq.cm per s, four orders of magnitude less than the corresponding rates observed for the Earth and Mars. Helium has been positively detected for the first time in the Venus atmosphere from the airglow emission at 584 angstroms. The thermal escape of helium would be extremely slow at an exospheric temperature of 400 K although escape may proceed by a variety of non-thermal processes including capture by the solar wind. Atomic oxygen emission for Venus is a factor of 10 larger than that measured by Mariner 9 for Mars in 1971/72. The larger Venus concentration may indicate a comparative absence of rapid vertical mixing in the Venus upper atmosphere. As expected, atomic carbon turned up as a trace element formed by photochemical reactions involving CO_2.

There is, however, a puzzling observation of an intense emission centred at 1350 angstroms. The radiation is extensive and is detectable on both the day and night sides of the planet. Its cause remains a problem for the future.

A NEW FACE

The images of Venus in the visible and ultraviolet returned from the Mariner 10 flyby have added a new dimension to our knowledge and understanding of the structure of the visible clouds and the motions on the Venus stratosphere. The spacecraft obtained a total of 3400 frames during a period of eight days at resolutions ranging from 100 m to 130 km. The best Earth-based resolution is approximately 250 km.

The global view of Venus in ultraviolet light (Figure 1) revealed a dark belt near the equator suggestive of the classical "Y" feature observed from the Earth. These high-resolution images of the planet have three general characteristics: a mottled appearance full of small-scale (100 to 500 km) features in the equatorial zone surrounding the sub-solar point (Figure 2); streaky and banded structures in the higher latitudes of both hemispheres (Figure 3) and a strongly divergent flow pattern around the sub-solar point and symmetrical about the equator.

The cellular structures in the sub-solar region suggest the presence of large-scale convection. Other data from Earth-based spectroscopic studies and measurements on the Soviet Ven-era probes imply a major proportion of the sunlight is absorbed in a cloud layer whose top is at around the 100 mb level and may be the driving mechanism of the observed motions.

The observations by the Mariner infrared radiometer confirm that the Venus atmosphere appears opaque at a pressure level of just over 100 mb. The cloud-top temperature at this level is approximately 255 K. The radiometer observations also show that there is no temperature difference between the day and night sides of the planet at these deeper atmospheric levels.

The limb photographs apparently refer to a region much higher in the atmosphere and there is evidence of thin highly stratified limb hazes, with a top at about the 10 mb level (Figure 4). These haze layers which are at most 2 km thick are evident in the temperature profiles derived from the occultation data. This limb structure is indicative of a very stable region. These pictures also suggest that layers of particulate matter are present in the Venus atmosphere above the ultraviolet clouds. The motions in the Venus atmosphere observed at the ultraviolet wavelengths, are therefore taking place in the upper troposphere/lower stratosphere region.

Recent optical studies of the Venus clouds, and spectroscopic studies of the composition of the planet's atmosphere, indicate that the clouds themselves are composed of sulphuric acid droplets of mean radius one micrometre. The particle size is uniform over the planet and quite uncharacteristic of terrestrial clouds. It is, however, more characteristic of aerosols which form in the terrestrial stratosphere.

The light regions we observe are therefore the higher clouds and the darker regions refer to lower cloud levels in the Venus atmosphere, whose composition and structure are unknown at this time. The maximum contrast between the major light and dark ultraviolet regions is 30 per cent. Contrasts in mottled areas and streaks, and the temporal behaviour of these markings, can be accounted for by small changes in the distribution of sizes of the sulphuric acid particles in the cloud.

The sub-solar disturbance (Figure 3) of the equatorial region, characterised by cellular features, appears to play a fundamental role in the upper atmospheric motions. The larger (500 km) less distinct cells are bounded by dark edges, while some appear polygonal in shape with considerable interior structure. These cells seem to last only a few hours. They are found to move with the wind and change markedly over a 2-hour interval. The sub-solar disturbance extends at its widest over $\pm 20°$ of latitude and at least 80° in longitude. This disturbance is locked to the Sun-Venus line and it is continually regenerated therefore, probably in response to the maximum solar heating. It is a region of high pressure, and, because the pressure falls off in the poleward directions, the normal zonal winds flowing parallel to lines of latitude are accelerated towards the poles. The spiral streaks may be interpreted as associated "jet streams". The kinetic energy of these motions is eventually dissipated as polar vortices at low pressure.

The interaction of the zonal winds with the sub-solar disturbance gives rise to bow-shaped waves. They seem to be a sign of the imbalance between the pressure excess in the sub-solar area and the mean zonal flow. In the equatorial zone, outside the sub-solar disturbance, light and dark features appear to move westward with velocities of approximately 100 m per s, which corresponds to the retrograde rotation period of four days. Earth-based observers have suggested that the period may be variable, and some have observed rotation periods of six days. At higher latitudes the flow is also primarily zonal, and there is some suggestion of shear in the polar ring which could mean an even higher zonal velocity. At 50° latitude the rotation period of the upper atmosphere may be as short as two days.

The return flow of atmospheric gas may occur at deeper levels in the atmosphere in order to maintain the planetary angular momentum balance. We do not know the vertical extent of these motions, whether the stratospheric rotation is a separate overturning cell, or whether it is linked somehow to the deep stirring of the huge Venus atmosphere. While subsequent observations may, however, assist us in understanding the meteorology of the present Venus atmosphere, we still face the problem of how this vertical distribution of motion arose in the first place.

The Mariner 10 ultraviolet images added a new dimension to the circulation of the Venus stratosphere, emphasising the importance of departures from a uniform zonal flow. To obtain a more detailed under-

standing of the circulation from these pictures will require evidence of poleward motions and knowledge of the variation of angular momentum with latitude. The pictures also imply a significantly different vertical temperature and wind profiles in the equatorial and polar regions. Consequently future space missions with carefully directed entry probes to different portions of the planet are essential to make *in situ* measurements of the atmosphere in order to reveal the mechanisms which drive the circulation, and its vertical extent. Balloons floating at different pressure levels would also provide invaluable information on the flow patterns and should be attempted at the earliest opportunity.

The US planetary programme plans a dual Venus orbiter and entry-probe mission for launch in 1978. There is also always the possibility future Soviet Venera systems with much larger spacecraft, comparable to those used at Mars in 1971/72 and 1974. We are approaching an exciting era of exploration of our nearest planetary neighbour.

EARTH

PETER STUBBS

Not only is the Earth, naturally enough, the planet about which we know most; it is also the most varied body in the solar system. The presence of water in large quantities has supplied us with extensive oceans; an active atmosphere; geological redistribution of material through erosion, transport and deposition to provide a rich and highly developed series of surface rocks — with a corresponding diversity of ecologies; and last — but by no means least — perhaps alone among our space neighbours, with life. An active interior has further embellished the Earth's surface with volcanic products, mountains, moving continents and growing ocean basins; and has supplied our space base with a relatively strong magnetic field. The latter, we now know from satellite measurements, has in turn interacted with the impinging "wind" of solar protons to enclose the Earth in the magnetic envelope we call the magnetosphere. Within this region many complex electromagnetic interactions go on. And within it, also, the Earth's magnetic field traps incoming energetic particles in the celebrated Van Allen Belts, thus shielding the Earth and its living organisms from the effects of otherwise harmful radiations. Nearer to the surface still, the magnetic field controls the form and behaviour of the layers of much less energetic charged particles which constitute the ionosphere, the radio-reflecting mirror which we employ for long-distance communication.

It is hardly surprising that the study of such a diverse planet should have fragmented into several sciences — geophysics, geology, oceanography, biology, meteorology, aeronomy and plasma physics. Indeed, we seldom think of practitioners of these sciences as true planetologists at all; while astronomers frequently ignore the Earth altogether when discussing the solar system. Plainly it is impossible to include in this short article any comprehensive survey of the Earth sciences. What I want to attempt to do is see our planet *as* a planet, and as a starting point for comparison with the other members of the solar system; and, to show how Earth-orbiting satellites have contributed to the completely new picture of the Earth which has emerged since the space age began.

A space mission to the Earth launched from another body in space would leave observers of the competence of, say, the Mariner 9 or Mariner 10 teams in no doubt about the presence of water as oceans on this planet. Had they experience of volcanoes, mountain ranges, extensive cities and even vegetation, they would be able to spot all these on their infrared pictures. While detailed geological interpretation of pictures from space may still be difficult, gross planetary features would stand out. The near absence of craters would indicate perhaps that extensive erosion has taken place on the Earth, and intelligent beings from elsewhere should quite easily be able to guess that the erosion is connected with the shifting weather patterns they could see, with seas, rivers and dust storms, and with ice-caps and mountain glaciers. The linear form of mountain chains and parallel fault systems — evidence of past earthquakes — would show them that we live on an internally active planet. And fly-by magnetometers and particle detectors — all standard equipment on today's planetary missions — would soon delimit the outlines of the magnetosphere, the ionosphere, and the Earth's field and its strength.

Terrestrial observers know most, not surprisingly, about the accessible surface features of their planet. But, for cosmogonic purposes it is arguable that the nature of the interior — the bulk of any body — is of more significance. Over the years it is remarkable how much geophysicists have been able to deduce about the internal structure of the Earth. To start with, the mean density of the Earth is some 5·5 g per cu.cm. Since the density of the heaviest surface and near-surface rocks is about 3.4 g per cu.cm, the Earth must have a much denser core — about 10 to 11 g per cu.cm. Various lines of reasoning suggest that this core is made up of nickel and iron. We know both that it is liquid, and its radius (3473 km) very accurately, from studying earthquake waves (an Earth-lander would be necessary to establish the internal structure for extraterrestrial observers). The liquid core extends out to about half the Earth's radius (mean 6371 km). Its liquid state follows from the fact that it will transmit only the compressional, or P, seismic waves, and not the elastic, shear, or S, waves.

Seismology, too, tells us that the Earth's crust is very thin — a mere 35 km beneath the continents, and 8 km beneath the oceans. The continents, made up largely of granitic and sedimentary rocks, with a mean density of 2.7 g per cu.cm, "float" like giant rafts in isostatic equilibrium with the underlying denser mantle; the oceanic crust, largely composed of basaltic rocks, is of greater density (2·8 to 3·0 g per cu.cm). Investigations by geophysicists and oceanographers in the years of the space age have revolutionised our picture of the Earth's crust, showing it to be mobile on a dramatic scale.

Between the crust and core of the Earth lies a thick mantle of crystalline material, almost certainly made up largely of dense ferro-magnesian materials. Earthquake, and man-made explosion studies show that, while the

mantle is not layered so regularly as to be laterally homogeneous, there are indications of further stratification within it. Many workers believe that such discontinuities represent physical phase changes wrought by pressure and temperature, rather than any significant chemical differentiation within the Earth. There is indeed one, perhaps extreme but not impossible, view that the liquid core is itself no more than such a change to a very high-density, possibly metallic, phase occurring at the enormous pressures that must exist half-way to the Earth's centre. If that is the case, and a nickel-iron core is to be ruled out, it obviously has important consequences for the Earth's origin, since our planet may always have been chemically homogeneous.

One space-age discovery, suspected as long ago as 1936 but only confirmed in 1970 by recording echoes of underground nuclear explosions, is that the Earth possess an inner, probably solid, core of radius 1217 km suspended within the liquid core.

Early theorists of the Earth's field had to suppose that something like a gigantic permanent magnet or lodestone lay within it. This idea was not implausible, since, as long ago as Elizabethan times, William Gilbert showed that the Earth's field was shaped much like that you get from a bar magnet. Early this century, however, Pierre Curie established that all magnetic materials lose their permanent magnetism at a specific temperature — for iron about 770°C. Inside the Earth the temperature rises on average at a rate of some 30°C per km. At the centre of the Earth the Curie point of iron or iron-nickel would be well and truly exceeded.

The problem of the origin of the Earth's magnetic field was solved by supposing the core, now known to be liquid, to be also an electrical conductor — apparently a liquid metal. Within such a system it is possible to envisage a liquid dynamo with self-energising "field coils", loops of liquid carrying electric currents which produce the magnetic fields to excite other interacting loops of current by induction, and vice versa. Such a dynamo could have been kicked off in the first place by an interplanetary magnetic field. The Earth's field is simply the external part of the dynamo's field. Plainly the existence of a magnetic field around any planet can tell us a good deal about its interior.

Theoretical arguments reveal clearly that a planetary fluid dynamo is strongly dependent on the rotation of the planet (the Coriolis force plays a dominant role) and, on average, would be expected to produce a dipole field aligned along the axis of rotation. The skewness of Jupiter's magnetic field is thus a fascinating anomaly. Planets without sufficient rotation — Venus may be a case in point — would soon dissipate their fields, even if they possessed fluid, conducting cores. And small planets such as Mercury (or the Moon) are simply unlikely to be still hot enough to enclose a liquid core, even if they were once so.

Looked at historically, through the record of "fossil" magnetism frozen into successive rock formations down the aeons, the Earth's field has one especially unexpected property, a property which leads directly back to the subject of the Earth's crustal mobility. Roughly once every 200 000 years, but not regularly, the field appears to have switched its direction through 180°. These magnetic reversals flipped the field over quite sharply. That this behaviour is quite plausible is borne out both by theoretical modifications to the models, and by actual experimental dynamos which exhibit similar instability.

Returning to the Earth's crust, the space age has seen an enormous development of oceanographic work that has led to much more detailed maps of the three-quarters of the Earth that are water covered. The ocean floors are now seen to be quite different structurally from the continents. The major oceans are divided up by a pattern of interlinked oceanic ridges, such as the Mid-Atlantic Ridge which bisects the North and South Atlantic oceans throughout their length. These ridges are repeatedly offset laterally by very long shear faults. Crumpled mountain ranges typical of continents are entirely absent. Foundered pieces of what appear to be former continental material occur in patches. The reality of the oceanic ridges is attested by extensive geophysical measurements and core samples obtained by the US Deep Sea Drilling Project's now famous drill ship Glomar Challenger. Beneath the layer of oceanic sediments which covers most of the ocean floor and lies up to 1·5 km thick, the ocean crust appears to be made of basaltic submarine lava flows and other volcanic material perhaps 1 to 2 km thick. A 5 km underlying crustal basement may be composed of coarser-grained gabbroic rocks.

The exciting discovery that has altered our whole picture of crustal events is that the ocean floors seem to be spreading outwards on either side from the oceanic ridges at rates of anything up to 10 cm per year. The ridges represent part of the boundaries of extensive crustal plates, boundaries in this case along which new crustal material wells up from deep within the Earth's mantle, arrives at the surface as volcanic rock, and extends the ocean floor sideways as it does so. The key piece of evidence for this revolutionary hypothesis, the theory of plate tectonics, comes from measurements of the small magnetic anomalies due to the permanent magnetism of ocean floor rocks, which are superimposed on the overall configuration of the Earth's magnetic field. These anomalies show a striped pattern parallel to, and on either side of, all the major ocean ridges. The pattern on one side of a given piece of ridge is the mirror image of its fellow on the opposite side. Here, it appears, we have pairs of vast sea-floor magnetic tapes flowing ponderously outwards and recording for posterity, imprinted within the lavas, the reversals in direction of the Earth's magnetic field, as they occur. Patterns from widely separated corners of the globe match. The whole process is corroborated by a mass of other data, not least by the actual dating by radio-nuclides of core samples from ridge flanks.

The plate tectonics theory currently sees the globe as made up of seven major plates and a number of smaller ones. Continents form part of specific plates, and the elbowing for space which takes place as new crustal material is injected along ocean ridges, is accommodated — as, for example, along the Pacific coast of the Americas — by underthrusting and descent of one plate beneath another. The crumpling of mountain ranges further compensates for crustal overcrowding. (See Plate 20)

Plate tectonics satisfactorily accounts for the break-up and drifting of continents. But the big remaining question — and that of the most planetary significance — is what drives this massive piece of global machinery. Internal radioactive heat presumably supplies the energy. Some kind of sub-crustal convection currents form the most plausible mechanism; but there are difficulties, such as those posed by layering in the mantle.

Only one other planet has so far revealed any indication of a similar process — Mars. Some workers have suggested that Mars is now at a stage similar to that of the Earth before break-up of the first supercontinent, Pangea. Does the cratered southern hemisphere

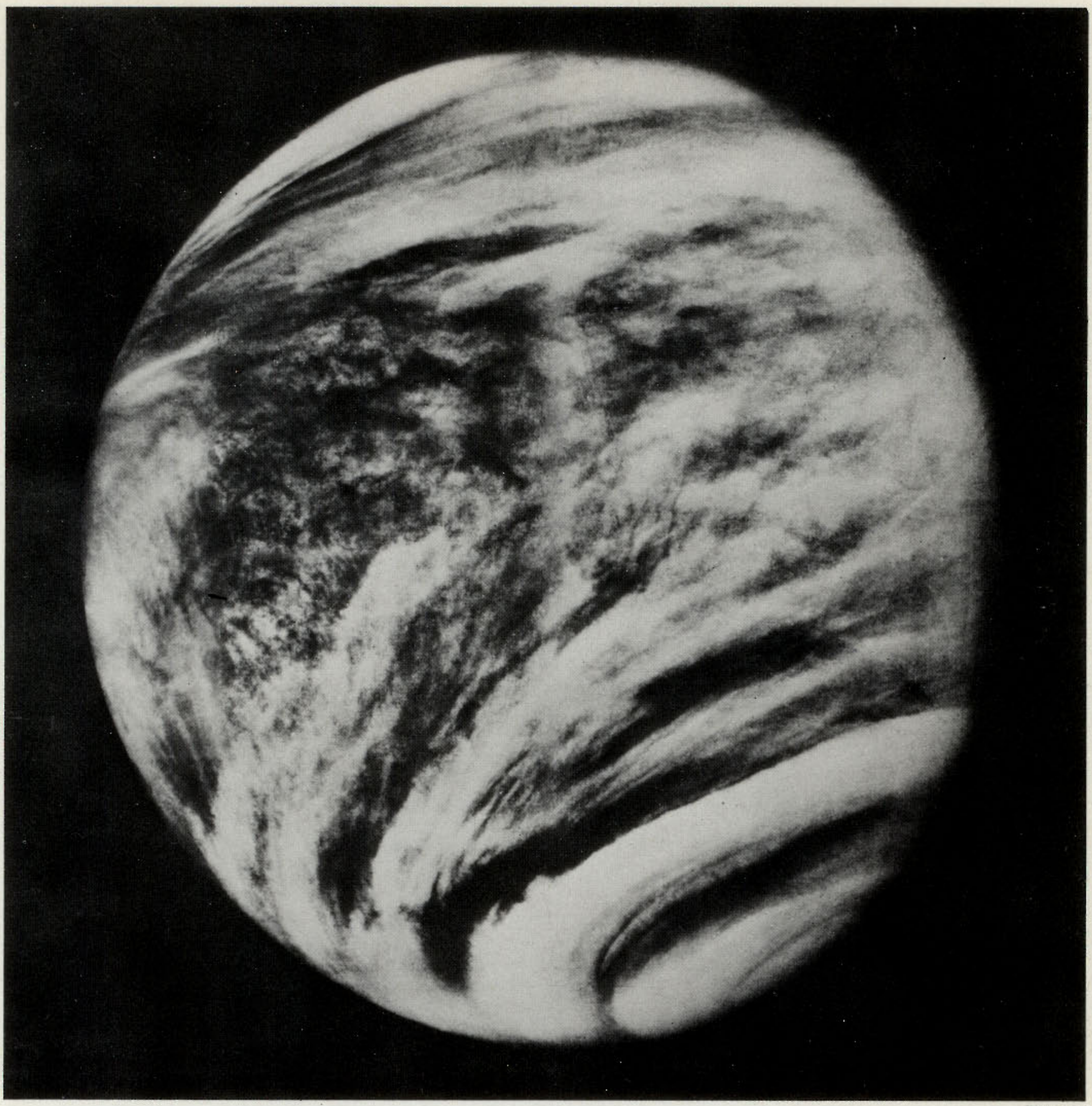


Plate 10

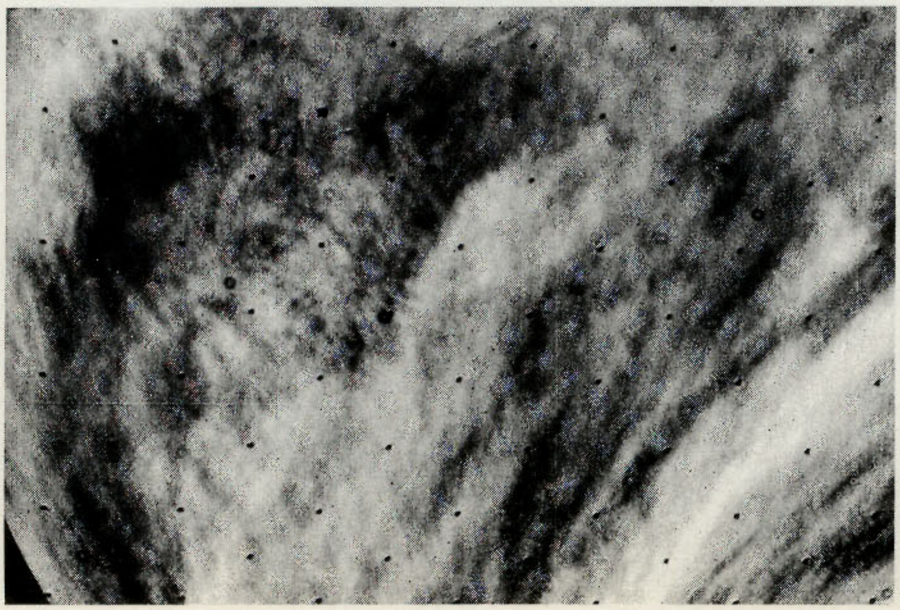


Plate 11

Plate 10 A view of Venus taken from a distance of 720 000 km on 6 February, 1974

Plate 11 The equatorial region of Venus from a distance of 880 000 km. The dark features at the top form part of a belt in the Venus clouds, which show features of rising and descending air currents. To the south of the belt are spiral streaks suggesting uniform flow around the planet toward the pole

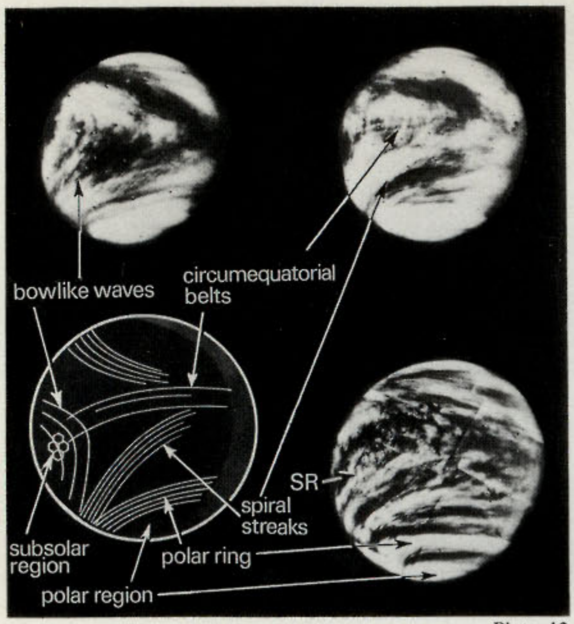


Plate 12

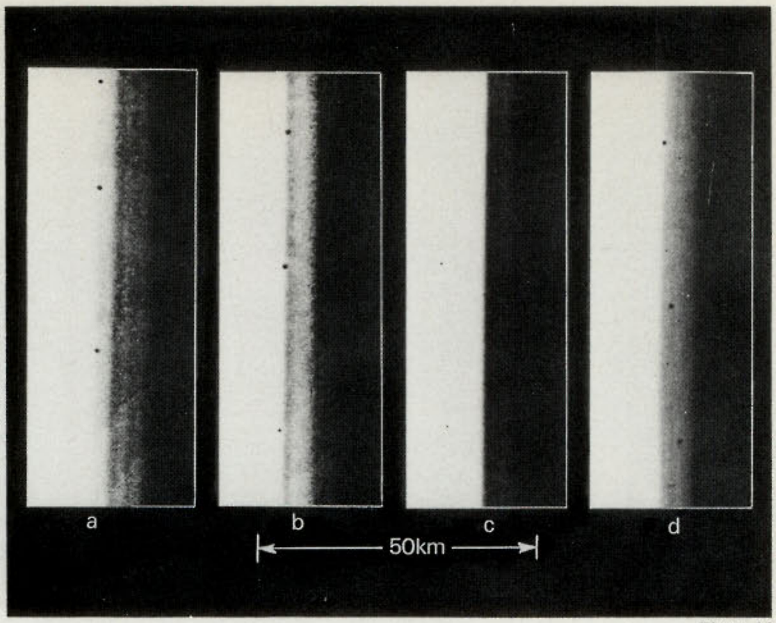


Plate 13

Plate 12 A summary of the Venus stratospheric flow regimes

Plate 13 Four views of the limb. Pictures (a) and (b) were taken through orange filter near equator and (c) orange, (d) ultraviolet photographs taken at latitude of 22°N.

Plate 14

Plate 15

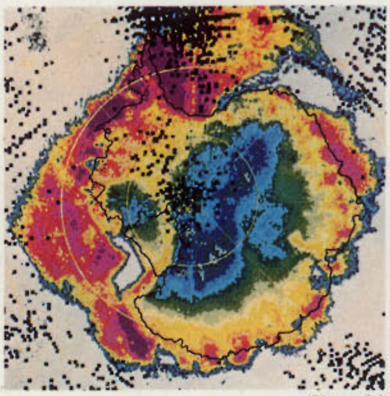


Plate 16

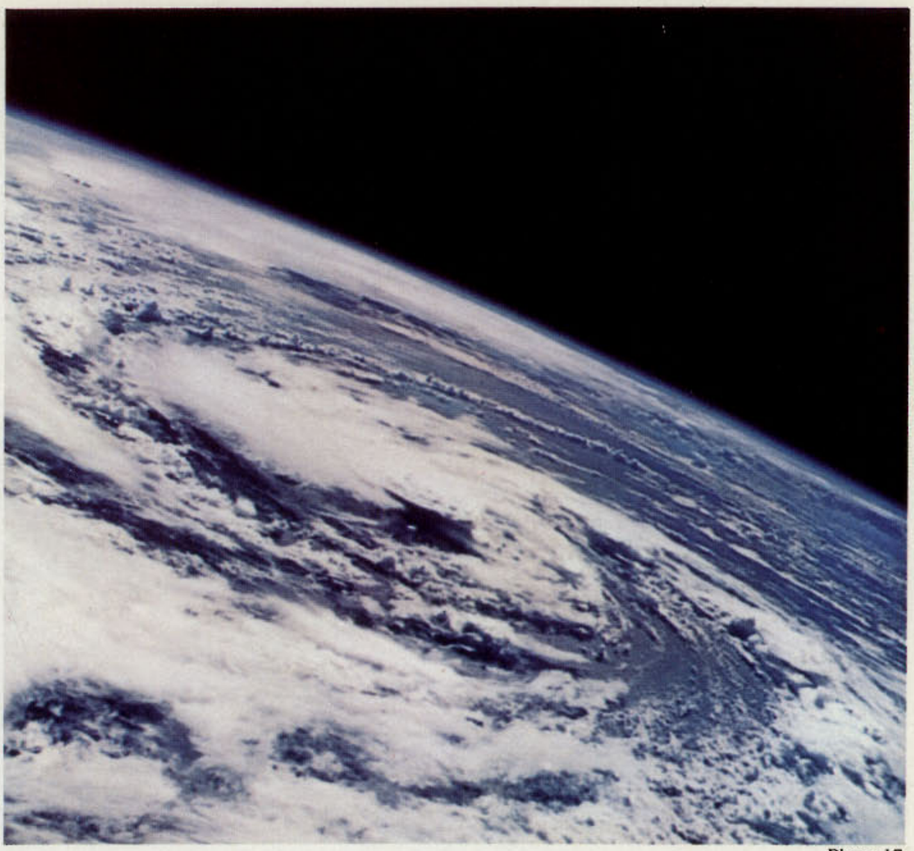


Plate 17

Plate 14 To the space traveller the Earth, as he approached it, would appear to be largely water covered through the whorled pattern of clouds. The outline of Africa can be discerned

Plates 15 and 16 Results from orbiting Earth satellites plainly reveal seasonal changes on our planet. Nimbus 5's scanning microwave radiometer produced these two "false colour" pictures of the Antarctic icecap, respectively in the southern hemisphere's summer (top) and winter (bottom). The white areas are water; the blue border is mixed sea, ice and water; dark blue represents glacier ice; yellow-green, thick glaciers or snow cover; and reddish-purple, new sea ice. Black dots are simply gaps in data

Plate 17 A justly famous Apollo 7 shot of hurricane Gladys west of Naples on 17 October 1968. A visiting spacecraft would easily detect that Earth has a vigorous atmosphere

Plate 18 Infrared imaging of the Earth's surface reveals highly organised patterns such as those made by these cultivated fields in California's Imperial Valley. These, and the thin canal visible at bottom right, might well be taken as signs of intelligent beings at work (Apollo 9 photo)

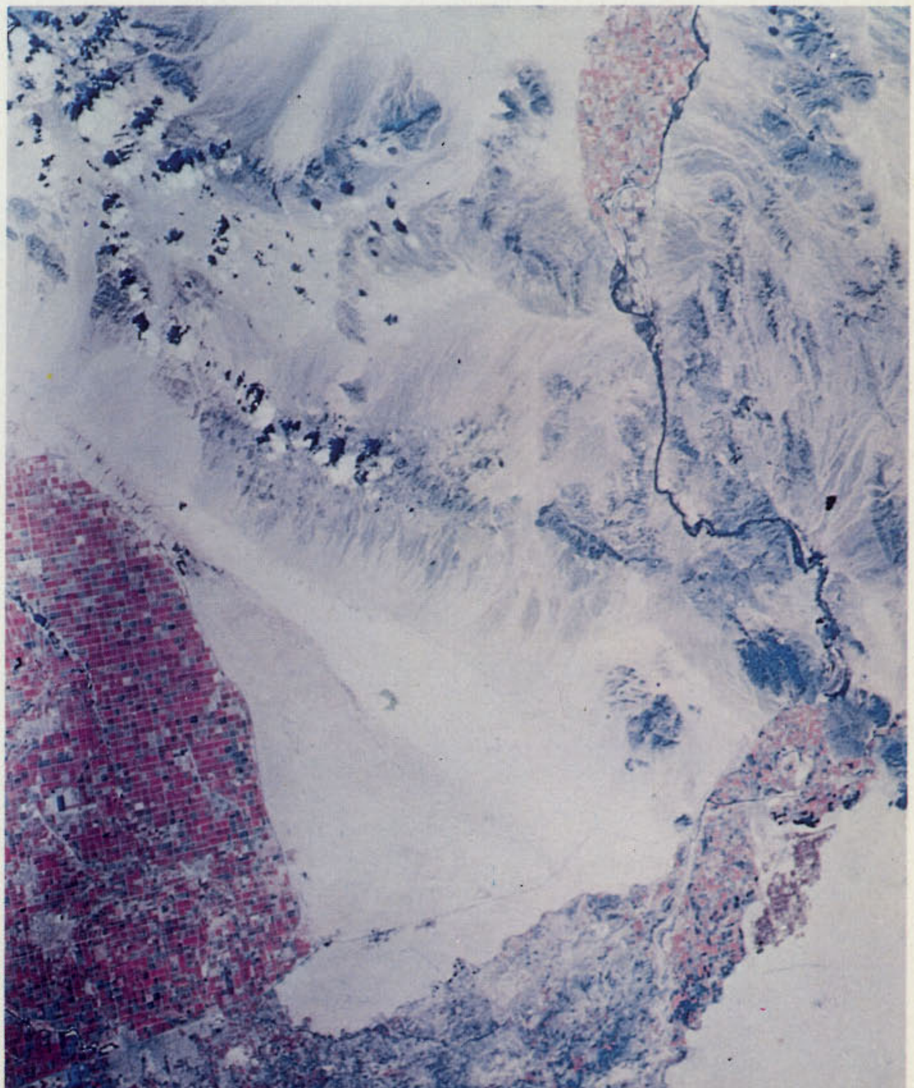


Plate 18

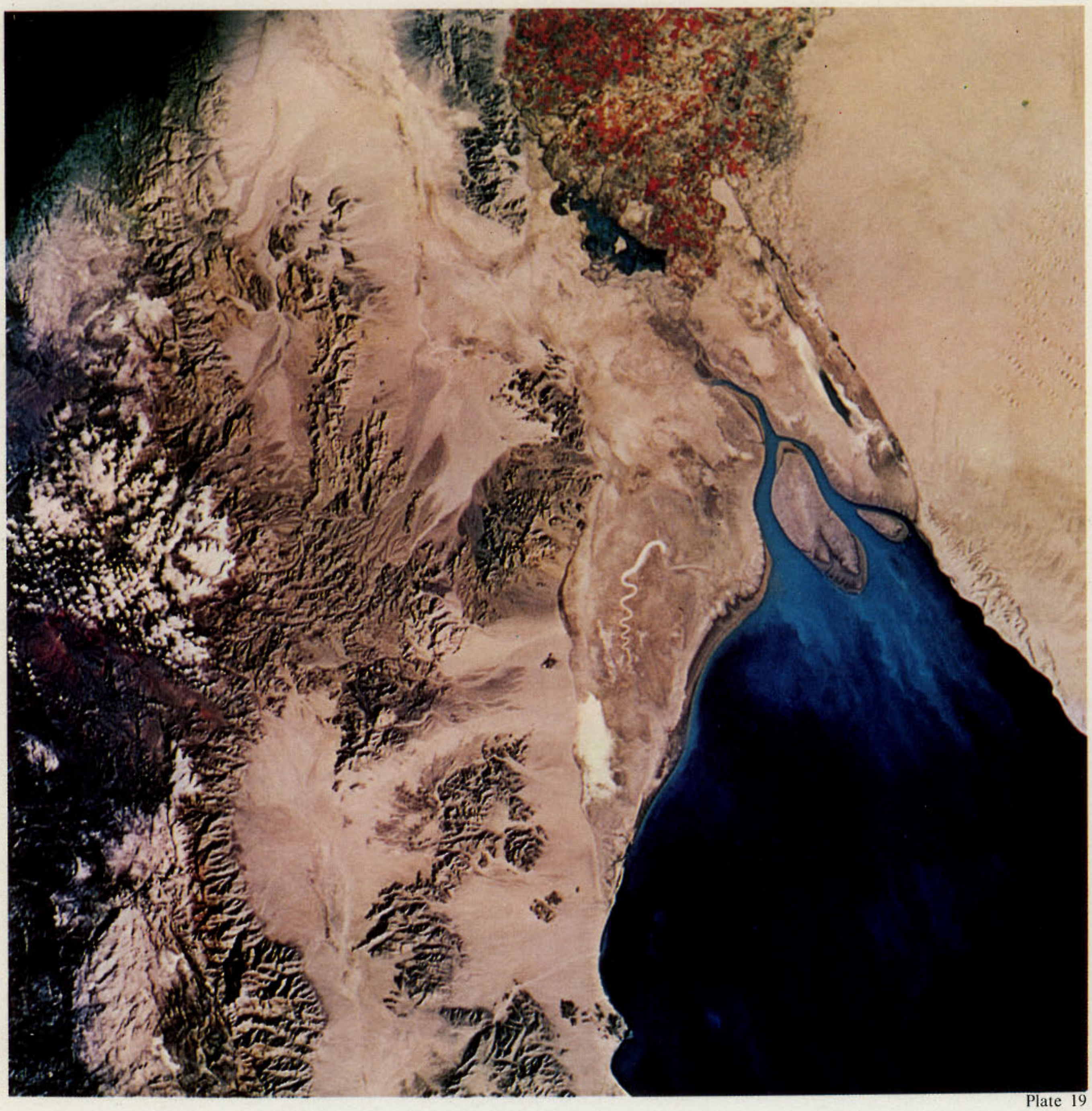


Plate 19

Plate 19 Another Apollo 9 photo of the mouth of the Colorado River and the northern end of the Gulf of California. Extraterrestrial visitors would soon learn that Earth has rivers and suffers stream erosion from the pattern of mountain gullies. There is also a hint of folded geological structures at left centre

Plate 20 The Earth's major crustal plates

Plate 21 The shape of the Earth referred to an ideal ellipsoid. Heights in metres

Plate 20

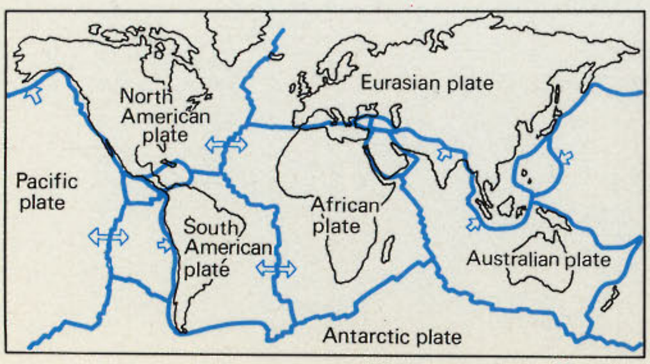
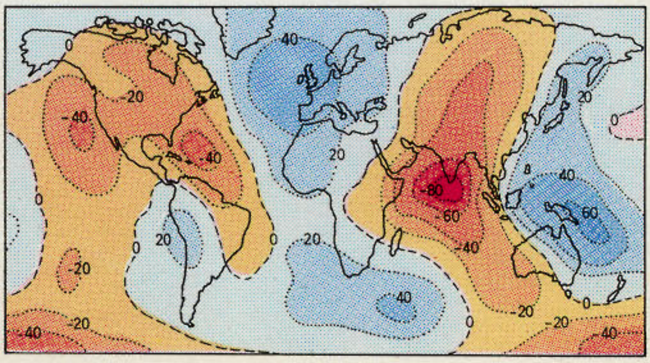


Plate 21



represent such a supercontinent; and the much smoother northern hemisphere, a primordial waterless Martian "ocean"?

Weather satellites have given us the first overall pictures of Earth's weather systems on a large scale; and are now paving the way to total monitoring of atmospheric convolutions, and temperature, pressure and humidity changes. Other satellites orbiting the Earth have told us a lot of new things about the ionosphere and upper atmosphere — especially about chemical composition, ion and electron densities and temperatures, and the daily variation of all these factors as the Earth's rotation switches the solar radiation on and off and varies the degree of ionisation, say, or the altitudes at which certain phenomena occur. Still higher satellites have provided a comprehensive structure of the magnetosphere, revealing that the Earth's magnetic field interacts with the solar wind to produce a sharp bow shock on the sunward side and a long magnetic "tail" in the shadow.

All the Earth orbiters have incidentally supplied data on the details of the Earth's shape. To a first approximation the Earth is, of course, a sphere. In fact, we know it to be an ellipsoid of revolution, flattened by 21 km in 6378 km at the poles. This ellipsoid is very nearly of the shape which would result from the hydrostatic balance of gravity versus centrifugal effects (The equator, in fact bulges by approximately 200 m too much.) Precise tracking of artificial satellites, however, has now not only confirmed that the Earth is slightly pear-shaped — its southern hemisphere is fatter than its northern — but has also revealed for the first time, a number of other bumps and dips which gravitationally deflect the trajectories of the satellites by small amounts (Plate 21). What is their cause? Are they relics from the Earth's formation? One suggestion is that "highs" may be the tops of the upwelling subcrustal convection cells that cause plate movements. Geophysically such shape measurements offer a new space-age challenge to the planetary scientist studying the Earth, the Moon, and, more recently, Mars, all of which have now been ringed by orbiting spacecraft.

MOON

THOMAS GOLD

The origin of the solar system — our strange and puzzling home in the universe — is not yet understood. There are very many clues, some strikingly clear, others hazy, about the events that must have taken place, about 4500 million years ago, that put together the planets and their satellites, and set them on their orbits. While these clues confine the speculation, they have not yet added up to a clear picture. We still do not know whether it was a strange and unlikely chance that was involved, or whether the millions of other stars like the Sun must all be expected to have similar systems around them. Are the materials we have here the common building bricks for planets in other solar systems? Are there lots of planets with rocks and water and an atmosphere? Is the speculation justified that life is abundant on innumerable other planetary systems?

The scientific space programmes of the US and the USSR were of course designed with an eye on these great questions, and it was clear from the outset that the Moon should be a prime target. Firstly, it was the easiest alien body to reach. Not having any wind or water, erosion would not have destroyed the record of past events. Internal upheavals that shifted, contorted and overturned much of the Earth's surface seemed to have been absent on the Moon — there are no signs of any large distortions in all the many ring-shaped structures. For these reasons there were many guesses that we would find there the geological record that is missing on the Earth, of the earliest periods when these bodies were forming: the geologic record of the solar system, not just one of its bodies.

Now, at the end of the Apollo programme, we have a great deal of information about the Moon. It bears out completely the view that it has a very ancient surface. Very few rocks can be found on Earth that are as old as each one of the lunar ones that were brought back. Nuclear age dating shows that the soil and the rocks became the solids they are between $4\frac{1}{2}$ and 3 aeons ago (one aeon is one thousand million years). $4\frac{1}{2}$ aeons is also the age of the oldest meteorites that have been found, and those in turn show clear evidence of radioactive processes having taken place within them, that could not have persisted for more than a few tenths of an aeon after the same matter suffered the nuclear processing that occurs only in an exploding star. There is good reason, therefore, for considering the time around $4\frac{1}{2}$ aeons ago as the time of formation of the solar system, and the Moon bears evidence that it is not much younger. Its surface is really old enough to contain all the evidence that we are looking for, but if it does, no one knows yet how to read it clearly.

Several quite different possibilities are under discussion at the present time as to how the Moon might have formed. That the Moon and the Earth were formed as one body and were subsequently torn asunder, or that they formed simultaneously from a common cloud of material, is not favoured by the chemical evidence for the Moon. Lunar materials all seem to show marked similarities as a group, and marked differences from the common terrestrial materials. This is so both for abundances of common elements and also for abundances of elements that occur in trace amounts only (Figure 1).

In such theories it would of course be necessary to suppose that the Moon had made its way from a close orbit of the Earth to the more distant one it now occupies, but this is not a problem. One understands clearly how the tides that the Moon raises on the Earth deform the liquid and solid parts of the Earth, and how this in turn causes the Moon to spiral outwards. There are uncertainties in the detailed calculations of the effect, but a time between 5 and 2 aeons would be sufficient to push the Moon out to its present orbit.

Other theories of the formation are the capture of a complete Moon that formed elsewhere, or the capture of many small particles into orbits encircling the Earth, that then accumulated into a single Moon. The capture of a complete Moon is theoretically possible, and there

have been detailed discussions how, with the help of enormous tides raised on the Earth during an initial close encounter, such a capture might have been achieved. But even if the capture process is a possibility, it is an extremely unlikely one. A very small range of initial orbits only would lead to capture, rather than to a direct collision with the Earth, or a mere perturbation and escape. One can argue against such a theory on the general grounds that there are some 30 other satellites in the solar system to be accounted for and that capture cannot be used to account for the majority of them. One clearly needs a theory that represents a probable process that would put satellites in orbits surrounding planets.

The accumulation of dust or chunks of material in orbits encircling planets is the most helpful one from this point of view. Saturn's rings give an example that such accumulations can occur, although in that case a little too close to the planet to accumulate in turn into bigger sized objects. Perhaps whenever such rings occurred a little further out from a planet, they did form into satellites in the course of time, and that is why we don't see such rings any more.

In such a theory it is by no means clear that the Moon would have formed directly as a single object, collecting up all the material of the ring. It is quite likely that in the first place many objects would have snowballed in different lanes, and that subsequently, and perhaps over long periods, their orbits were influenced by each other, and by the tides they raised on the Earth, in such a way that they eventually all collided with each other, and that the major body so formed swept up or expelled the remaining debris.

How will lunar observations prove or disprove such theories? How will details of the lunar surface shed light on such processes?

The greatest problem that has confronted the lunar investigators is concerned with basic assumptions. Must one explain how the Moon formed out of the original mix of the elements available in the early solar system? In that case, one has to explain how the chemical sorting occurred within its body, to generate the particular minerals locally, that are now found there. It is known that these minerals do not represent the kind of substance that might have condensed directly in the early solar system, but rather a material that solidified from a melt on some planetary body, and that represents the lighter fraction and thus formed the upper crust. These differentiation processes are well known from the examples on the Earth, and it might therefore be considered that similarly on the Moon there must have been a period of extensive melting and freezing of the rocks. In that case, the evidence of the earlier accumulation processes would also be obliterated there, and only a small amount of late infall would have left its marks on the surface, causing the craters, and crushing up rocks into powder.

The alternative basic assumption would be to suppose that the materials now found on the lunar surface, whatever their chemical composition, represent the last epoch of the accumulation process. After all, one could hardly imagine a planetary surface to give a clearer indication of being shaped by infall than the Moon does. Three-quarters of its area is composed of indefinitely many overlapping craters, with many of them still showing clearly the details expected from the impact of debris of all sizes, falling in at astronomical speeds. Despite a careful search for areas of solid rock, and the selection of landing sites with this search as the prime criterion, no such areas were found. The pieces of rock that were sampled by the astronauts were all, without exception, separate chunks strewn around the lunar landscape (Plate 27), presumably by impact explosions; in no case were the rocks formed or congealed in the locations where they were found. The surface material almost everywhere was found to be a soil composed of a mixture of pulverised rock, just as one would expect of the surface of a body that had accumulated from the infall of solids.

The recent Mariner 10 spacecraft observations of the planet Mercury show its appearance to be remarkably similar to the Moon's (see photos p 14). There are also the same multiply overlapping craters, the same smooth looking low areas, the same patterns of lighter areas surrounding the fresher craters; and very similar dust must cover the surface, since the sunlight is scattered in just the same manner (Plate 22). But the interior of Mercury must be very different from the Moon. It is made of much denser stuff (mean density 5·4 g/cu. cm compared with 3·3 for the Moon) and the temperature

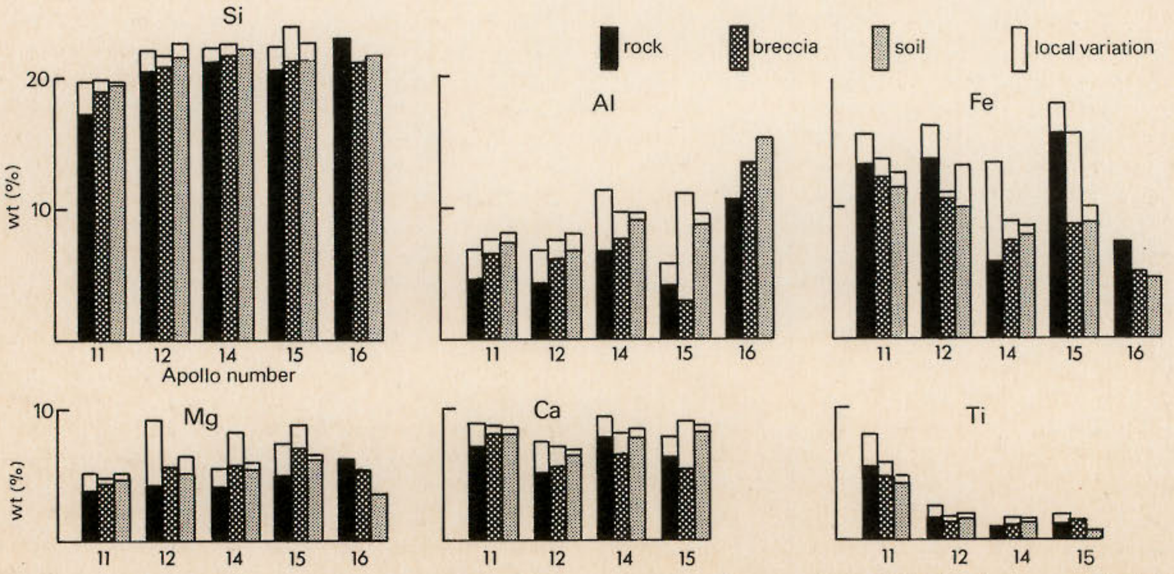


Figure 1 The different landing sites have shown significant differences in the abundances of the elements making up the powdery soil, the compression-welded breccias and the crystalline rocks. The proportions by mass of the six major elements are shown here, for five Apollo landing sites. Oxygen makes up the bulk of the remainder in each case. The abundance of titanium is characteristically higher than in terrestrial samples, and this, as well as several other compositional differences, argues against any common origin of the two bodies. (The data are selected from the chemical analysis teams appointed by NASA)

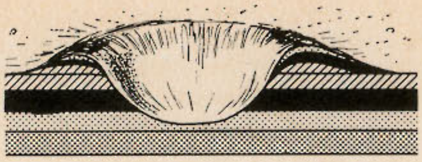


Figure 2 If a crater excavates material to a depth at which the composition is different, the blanket of ejecta will reflect that fact. (Indeed, studies indicate that there is an inverting effect, with the material excavated from the greatest depth appearing at the top of the new surface surrounding the crater.)

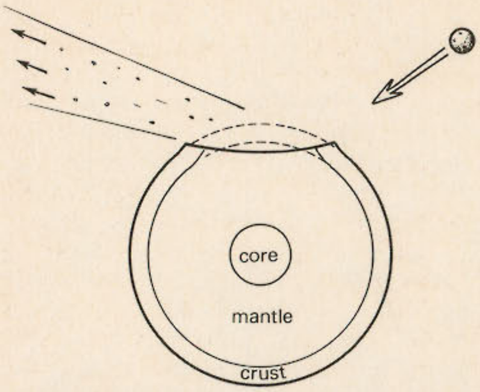


Figure 3 If a body that is differentiated into core, mantle, and crust is hit by a substantial other body, it may lose crustal material only, or crust and mantle, or, of course, it may be shattered altogether. In each case the debris will fill a particular range of orbits only, rather than contribute to a general mix in the solar system. Another body accreting material may thus acquire distinctive layers in succession.

regime in the interior is not likely to be similar. If the Moon's surface was dominated by internally caused effects, combined with only a small amount of later infall, as many investigators think, then would it not be a strange coincidence for Mercury's surface to match it so closely? On the other hand, if these are the surfaces that result from infall only, then one merely has to suppose that the interior circumstances did not have a large share in shaping the outside of either body.

But what can be said about the chemical composition of the Moon? Can one prove that it was locally melted and chemically rearranged, or could these processes have taken place elsewhere and earlier, so that already modified material came to fall in and form the outer layers of the Moon?

One can certainly prove that there has been some melting on the Moon. Many rocks that were brought to Earth are crystalline, clearly frozen magmas. But then such rocks would be expected to be made in the course of an impact history in any case. The largest impacts, such as made the huge circular basins on the Moon, must have generated pressure waves of such intensity that a depth of many kilometres of molten rock would have been generated over the area of the basin. Much later, when an overburden of debris had accumulated over the frozen magmas, some other impacts would dig down and keep bringing samples of this material up to the surface.

But would simple infall not have provided a uniform material covering the entire Moon? Perhaps some large pieces that fell in may have had their individuality, but surely the huge amounts of small particles must have coated the Moon with a uniform mix. How can the Moon end up with as much regional variation in the chemical composition as was discovered? (Plate 24.)

Each time a large impact generates a huge basin, material is excavated from a great depth and thrown over the surrounding areas. Mare Imbrium, for example, was probably dug down to a depth of 150 km at the instant of the gigantic impact. If any chemical differences existed vertically from the process of building up the Moon, then those are converted into horizontal variations by such an event (Figure 2). Vertical differences can of course result when different types of material became available at different times during the infall periods.

Could the chemical processing of the lunar materials have happened elsewhere before they built up the Moon? Nothing that we have learned so far is able to rule this out. Meteorites that we find give clear evidence in many cases of being debris of smashed up planetary bodies. Some of those bodies must have been hot enough for much material to have been melted. Differentiation processes similar to those that happened on the Earth must have happened on these parent bodies. One class of meteorites has indeed a composition that is quite similar to that of the surface of the Moon, although not absolutely identical with it. So here also there is no clear-cut answer to the dilemma. What meteoritic debris from what particular parent bodies populated the orbital lanes that made the last addition to the Moon is a very difficult matter to assess. The meteorites we now find represent only a tiny fraction of the material that was once there to build the planets, and it is just the material that remained by chance on orbits not yet swept up by the major bodies. Many other classes of meteorites might once have existed or still exist, but we do not know them because they have already been swept up, or because the Earth does not happen to intersect their orbits at the present time. Thus, the meteorites also do not give a clear answer. Chemically differentiated material is common among them now, and may have been common in the early times. Debris from early collisions must have had a distinctive chemical composition in each case, and would have been scattered onto particular orbital lanes, which were then swept up in some arbitrary order by the final bodies (Figure 3).

We are thus left with the basic problem that must dominate the entire discussion. Is the detailed lunar chemistry the result of lunar processes, or the result of the final stages of the building of the Moon? Are we looking at an Earth-like body that obliterated the record of its formation process, or are we looking at that record but, because of its complexity, failing to understand it?

If neither the chemical composition nor the overall appearance can give a clear answer between these alternatives, what other evidence is there to look to? The subsurface structure can be deduced to some extent from the study of the very faint moonquakes that are recorded, and also from the seismic signals resulting from occasional meteorite impacts and from the impacts of abandoned spacecraft. Also, radar and other radio-frequency methods can be used for depth sounding of the lunar ground. If the chemical differentiation had occurred on the Moon, then one would imagine that a layer of bedrock of frozen lava would generally lie underneath the dusty surface. The dust would only be a coating derived by the pulverising action of large and small impacts. On that basis, the flat floors of very many large craters, and of the low-lying areas, are thought to be the lava beds. On the other hand, if the surface represents the build-up of material from infall, powder in various stages of compaction may extend to a depth of many kilometres.

The seismic signals show the Moon to be totally different from the Earth. Firstly, it is internally about 1000 times quieter: moonquakes are weak and rare.

This of course fits well with the observation that the surface shows little evidence of distortion. The second big difference is that internally caused moonquakes come frequently, and perhaps predominantly, from a very great depth, approximately halfway to the centre of the Moon; that is, a depth between 700 and 1200 km. On the Earth the great majority of 'quakes originate shallower than 60 km and only very rarely have 'quakes been recorded from as deep as 700 km. It is thought that deep earthquakes are rare because the deep material is hot enough to flow plastically under stress rather than to break suddenly; this would suggest that the Moon is cooler inside.

The nature of the seismic signals on the Moon proved to be most remarkable and quite different from those that occur on Earth. Here an impact or an explosion 100 km away would generally produce a characteristic sharp "first arrival" signal after perhaps 20 seconds, followed by the slower transverse waves, with the whole signal being over in not much more than a minute. On the Moon, in the same circumstances, a noisy signal builds up slowly, with no very sharp beginning, takes between 5 and 10 minutes to rise to maximum amplitude, and then about 1 hour to fade away (Plate 23).

What can be so different on the Moon? On the Earth there is almost everywhere a solid sheet of bedrock that propagates the seismic signal. This is evidently not the case on the Moon. Those who believe that bedrock is present have to say that it is heavily smashed up and fragmented in a way that it never is on the Earth, so as to create a slow and reverberant transmission medium. The alternative, very acceptable for the interpretation of the seismic data, is that a soil, like that found on the surface, exists to a depth of several kilometres, gradually or abruptly increasing in compaction with depth due to the weight of overburden and the hammer blows of earlier meteorites.

Earth-based radar gives a clear indication that there is not a sudden transition from the top soil to broken-up bedrock at a shallow depth. Long-wave radar (at a wavelength of 7·5 m) would penetrate through the material of the top soil and show subsurface reflections down to a depth of at least 100 m and quite possibly 200 or 300 m. (Lunar soil is much more radar transparent than any terrestrial soil or rock.) Jumbled up pieces of rock would scatter the radio waves back with an intensity several times greater than is observed. Moreover, this rough subsurface would make the Moon more or less equally reflecting over the whole disk, just as the rough optical surface makes the full Moon more or less equally bright. The long-wave radar, however, shows the edge to be more than 100 times fainter than areas closer to the middle. The radar Moon is enormously limb-darkened. It is clear that there are no large areas on the Moon where a thin layer of the surface soil overlies coarsely broken-up bedrock. The alternative explanation of the seismic signal, in terms of deep deposits of a powder variously compacted, would agree with the radar data. So this evidence fits much better with the cold accumulation theory of the surface, than with the lava origin. The fact that no bedrock could be found in any of the Apollo missions would then also have a natural explanation.

Some investigators believe that the mere presence of big flat areas is sufficient to prove that huge lava outpourings have taken place. They also believe that some individual features represent the flow patterns of lava, or the outcrops of lava sheets on steep slopes. Comparable photography of areas of the Earth that are free from vegetation would have left no doubt about the existence of many lava flows. The lunar evidence is not nearly so convincing. Apparent "flow fronts" of supposedly congealed lava (Plate 25) are seen on the flat ground and are regarded by some as convincing. On the other hand, entirely similar flow fronts are seen around the base of very many remains of old crater rims, and for them nothing other than a surface erosion and transportation process, albeit it of unknown nature, can be invoked (Plate 26). On a time scale of 4½ aeons, very minor processes can have been sufficient to cause quite large changes in a dusty surface. It is very difficult to be sure what moved the dust, although various electrostatic processes would seem perfectly adequate; but it is equally very difficult to be sure that no surface migration of dust could have taken place. Another feature claimed to represent bedrock at a shallow depth is an apparent ledge photographed by the astronauts when they looked across to the other side of the valley called Hadley's Rille. Again, this evidence is not very strong. The ledge was not sampled, and may well represent no more than a stratification in compaction of the powder. Compacted powder will give an appearance of fracture lines and planes that can be very similar to solid rocks, even though the forces necessary for the fracture may have been orders of magnitude smaller. On the opposite side of the argument we have the very many craters that are of quite remarkable perfection, being accurately round with a perfectly smooth bowl as the interior surface, and an absolutely level rim (Plates 30, 31). Many of those are in the size range from tens of metres to kilometres. A sheet of brittle rock breaks into much more erratic patterns.

There are many other lines of evidence that one can pursue. The slight variations in the local strength of gravity (Plate 28), measured through the perturbations of orbiting spacecraft, revealed the existence of the so-called "mascons", regions of higher density evidently underlying the large, flat-bottomed basins. Such a mascon requires the ground at a depth between ten and a few hundred kilometres to be quite strong, for otherwise the region would have sunk deeper in the long time since its formation. If huge amounts of lava had been poured out, one would suspect the ground just beneath to have been partly molten, and no rocks would then have the required mechanical strength. There is a great problem here with that explanation, while in terms of a basin subsequently filled by surface deposit, there is no need to think that the deep ground could not have been cool enough at all times.

Each of these many points can be debated, and the answers are not yet sure. Just as was the case in the early days of geological investigations of the Earth, one has a great deal of knowledge of facts, but as yet very little basic understanding. What we have seen is that the Moon is dramatically different from the Earth, and that we must therefore argue out each case from first principles and not by analogy with terrestrial investigations.

The next step must be to find a clear way to decide between the two basic possibilities discussed here. If the Moon is a locally differentiated body, as many investigators believe, the information it can provide is limited in much the same way as the Earth's. However, if its surface material represents the last infall, the evidence it then provides is perhaps unexpected; but a possibility must not be rejected just because it would teach us something we had not foreseen. In that case, we would hope to learn a great deal from the Moon about the early solar system and the construction of the Earth and the other planets.

Plate 22

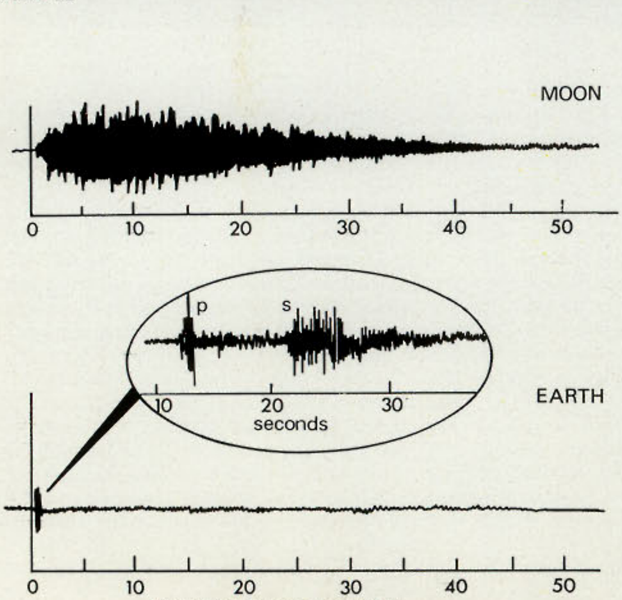


Plate 23

Plate 22 This view of the full Moon, taken as the Apollo 17 crew began to head for home, shows a large part of its far side. The striking similarity between the lunar surface and that of Mercury (see Figures 2 and 3 on p 14) argues for the treatment of the two surfaces having been alike. If both surfaces were mainly shaped by external effects, this similarity would be expected. The interiors, however, are likely to be quite different, and any volcanic activity would be expected to have been markedly different (in nature, extent, and timing of occurrence with respect to infall) for the two cases

Plate 23 Lunar seismic signals are very different from those on Earth. The signal shown in the top trace, from an impact approximately 100 km away (Apollo 12 seismic experiment), rises slowly and reverberates for one hour. In similar circumstances on the Earth the signal would have been almost all over in less than two minutes, while the lunar one has only just begun to rise. This great difference must mean the absence on the Moon of the good direct path for the sound provided on the Earth by solid coherent rock, and instead a sound propagation channel of very unusual properties: it must conduct sound much slower than solid rock; it must scatter sound waves to cause the reverberation; it must duct sound waves under the surface so that the energy is not lost too quickly by transmission downwards; and the dissipation of sound waves must be very low. A deep layer of compacted powder or thoroughly smashed-up rock have been discussed for this. (After G. V. Latham and others, Science, vol 167, p 455)

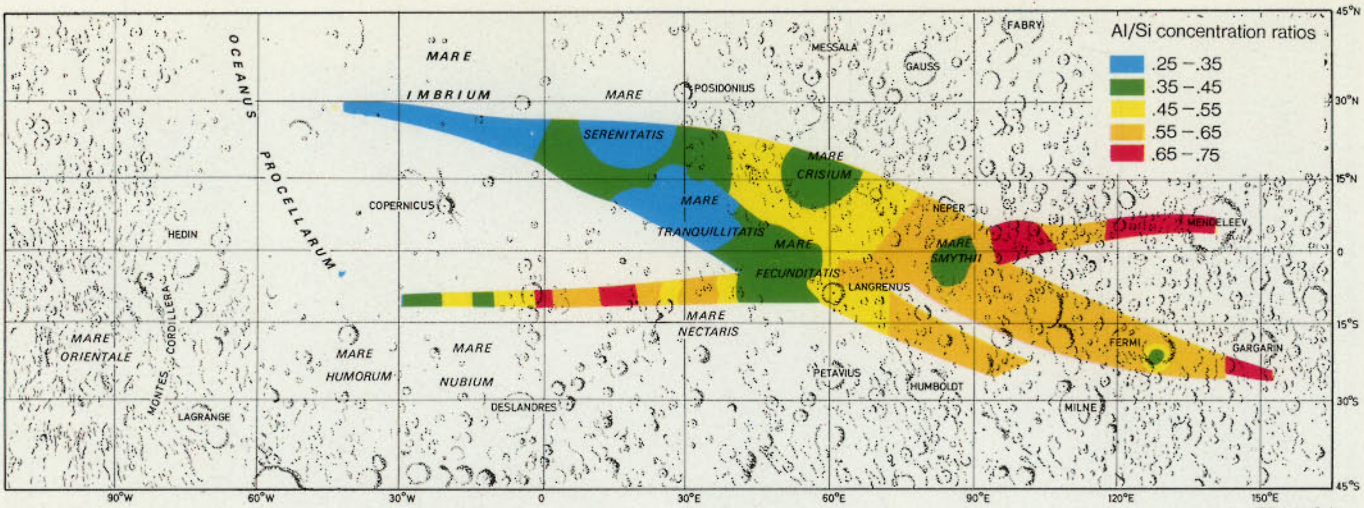


Plate 24

Plate 24 While the Apollo command module was in orbit around the Moon, instrumentation aboard it scanned the lunar surface for any X-ray fluorescence it might be exhibiting. The X-ray energies were analysed to identify the chemical elements in the surface materials. The swath across the Moon which the orbital telescope examined showed the aluminium-silicon abundance ratio (in the top few millimetres of the surface) to have marked regional variations, aluminium being generally more abundant on the high ground. Greater uniformity was observed with respect to most other elements. (Diagram from Proceedings of the Fifth Lunar Science Conference Geochimica et Cosmochimica Acta. Supplement 5, Pergamon Press, in press.)

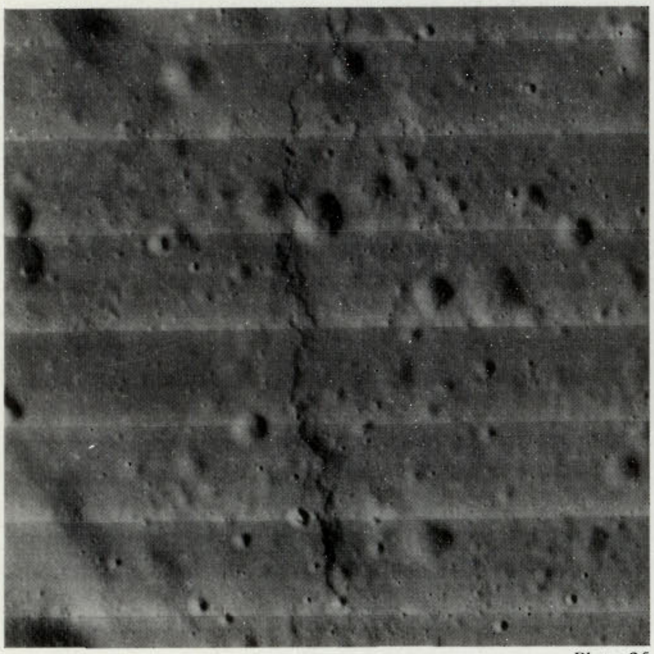


Plate 25

Plate 25 A "flow front" that has been interpreted as a lava flow arrested by freezing. It is on flat lunar ground, and the step is a few metres high. The way in which craters in the flow front are engulfed but not filled casts doubt on any genuine liquid as being the flowing medium. Craters appear to be merely coated by the "flow", and the general cratered surface looks much the same on both sides of the front (NASA Lunar Orbiter photo)

Plate 26 An area of flat "mare" surface from which protrude some old and heavily eroded mountains. At the base of each mountain the junction line with the mare ground has a characteristic profile — a "shoulder" — which must represent material that has been moved downhill and accumulated in this peculiar fashion. Some of these "shoulders" have a very similar appearance to the "flow-fronts" of Plate 25 especially in the manner in which they engulf small craters (NASA Lunar Orbiter photo)

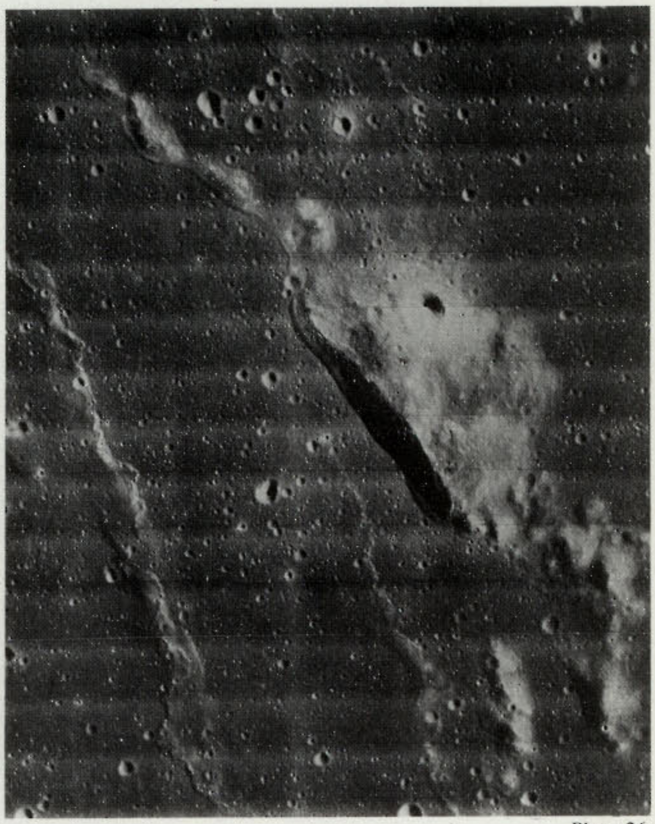


Plate 26

Plate 28 Gravity map showing mass excess and mass deficiency over lunar surface.

This information comes from the very precise observations of the orbits of spacecraft.

The map shows that the large circular basins represent a mass excess ("mascons"), despite their lower surfaces. Denser material must underlie them. Mare Orientale, the large feature on the left, which lies on the reverse side of the Moon, is a basin without much filling, and shows the features left by the gigantic impact. If it received a surface fill like the other circular maria, it would show the same positive gravity anomaly as they.

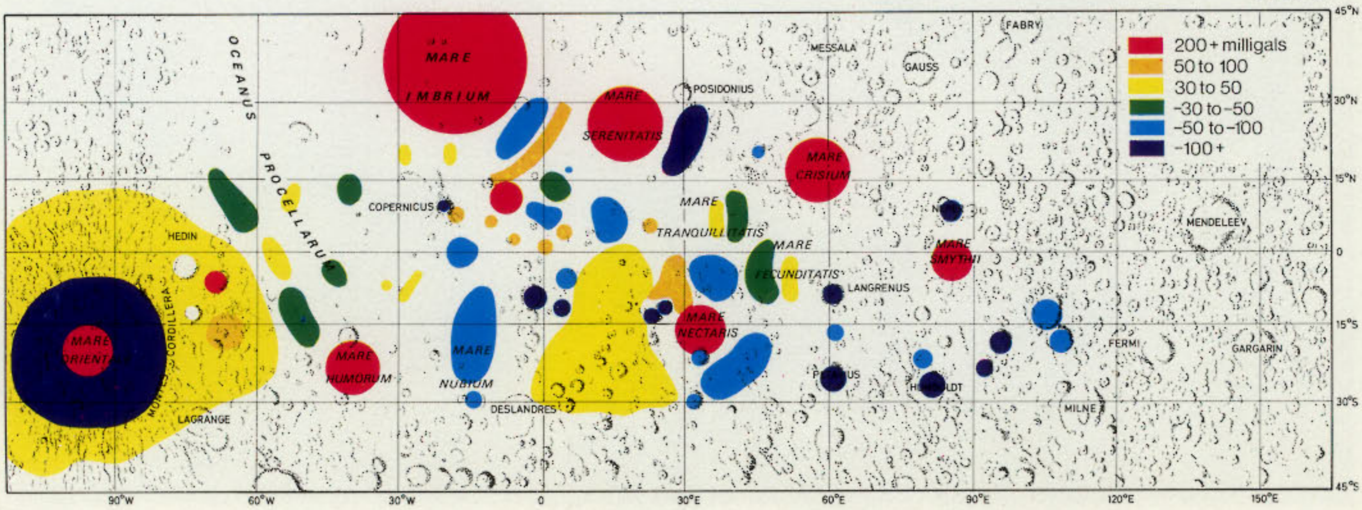
Density differences on this scale need not be due to differences in composition. The lunar ground may well be porous, as it is near the surface, to depths of many tens of kilometres, before the weight of overburden would crush out all porosity. The floors of basins have been subjected to the large pressures at the impact, and they will not have retained any porosity below. A basin with a denser floor and a surface fill of one to three kilometres would produce the observed effect.

Small craters are negative gravity anomalies, corresponding to the excavated material. (Diagram from Proceedings of the Fifth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 5, Pergamon Press, in press).

Plate 27

Plate 27 Astronaut H. H. Schmitt next to a large split boulder. Rocks encountered by the astronauts or photographed by the remote-controlled lunar orbiters were always found as separate pieces strewn over the surface, and usually partly embedded in the dusty soil. They appear to have been tossed to their present positions by impact events. No identification of crystalline rocks frozen in the place in which they now are, was made in the course of any of the Apollo landings (Apollo 17 photo)

Plate 28



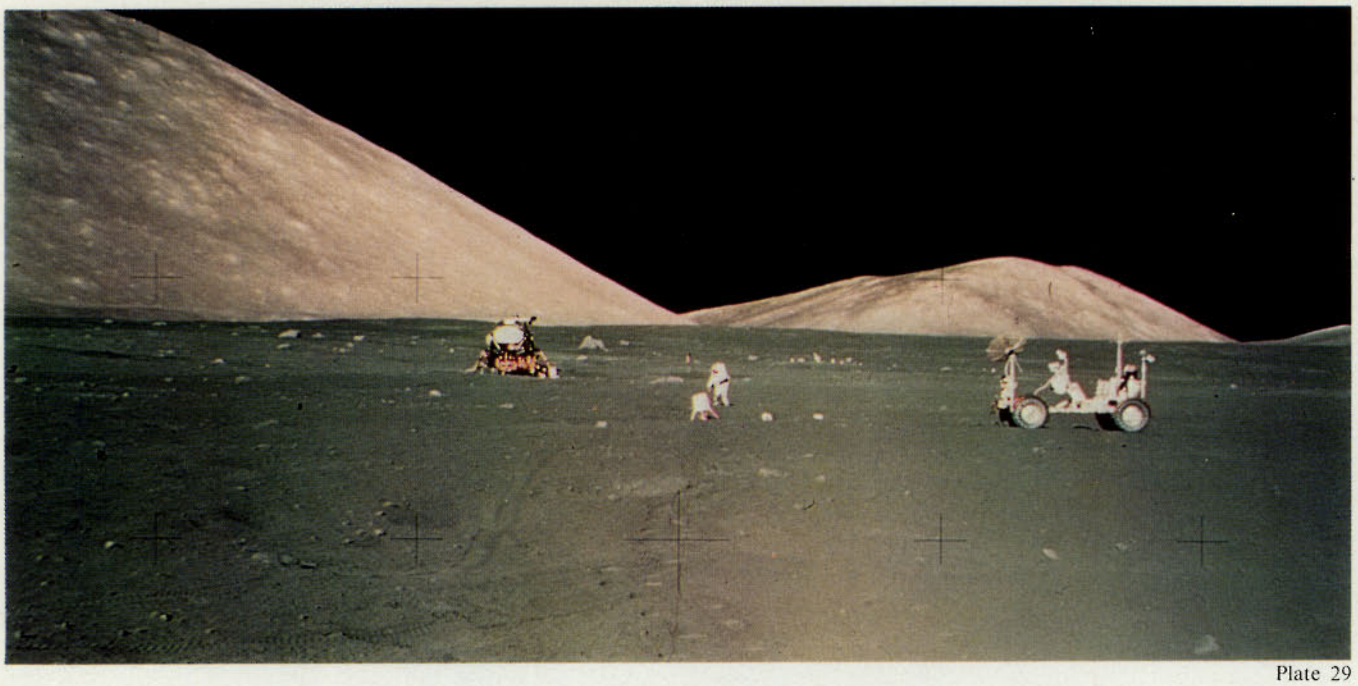


Plate 29

Plate 30

Plate 31

Plate 29 Astronaut Jack Schmitt at work at the Apollo 17 landing site in the Taurus-Littrow area of the Moon. The background consists of the South Massif and Family Mountains

Plate 30 Crater Schmidt, seven miles across, lies on the western edge of Mare Tranquillitatis (Photo: NASA, Apollo 10)

Plate 31 The crater seen here, International Astronomical Union *308, lies on the lunar far side. It is some 50 miles in diameter. Smaller craters testify to the good circularity displayed by many lunar impact features. This and the preceding photograph of crater Schmidt confirm that many craters are remarkably perfect circular bowls. Impacts in rocks usually generate shapes that show more pronounced fracture patterns, and solid rocks underneath powder would result in ledges and steps in the interiors of craters (Photo: NASA, Apollo 11)

Plate 32 This thin section micrograph of an Apollo 11 sample of lunar rock proves that some of the Moon's material, at least, is crystalline. The different colours are here produced by polarised light; several different minerals can be distinguished. The photograph was taken by Dr Klaus Keil of the University of New Mexico

Plate 32

Plate 33 Earthrise over the Moon's horizon. The crescent Earth had never been glimpsed before man landed on the lunar surface. This spectacular photograph was taken during the Apollo 12 mission

Plate 33

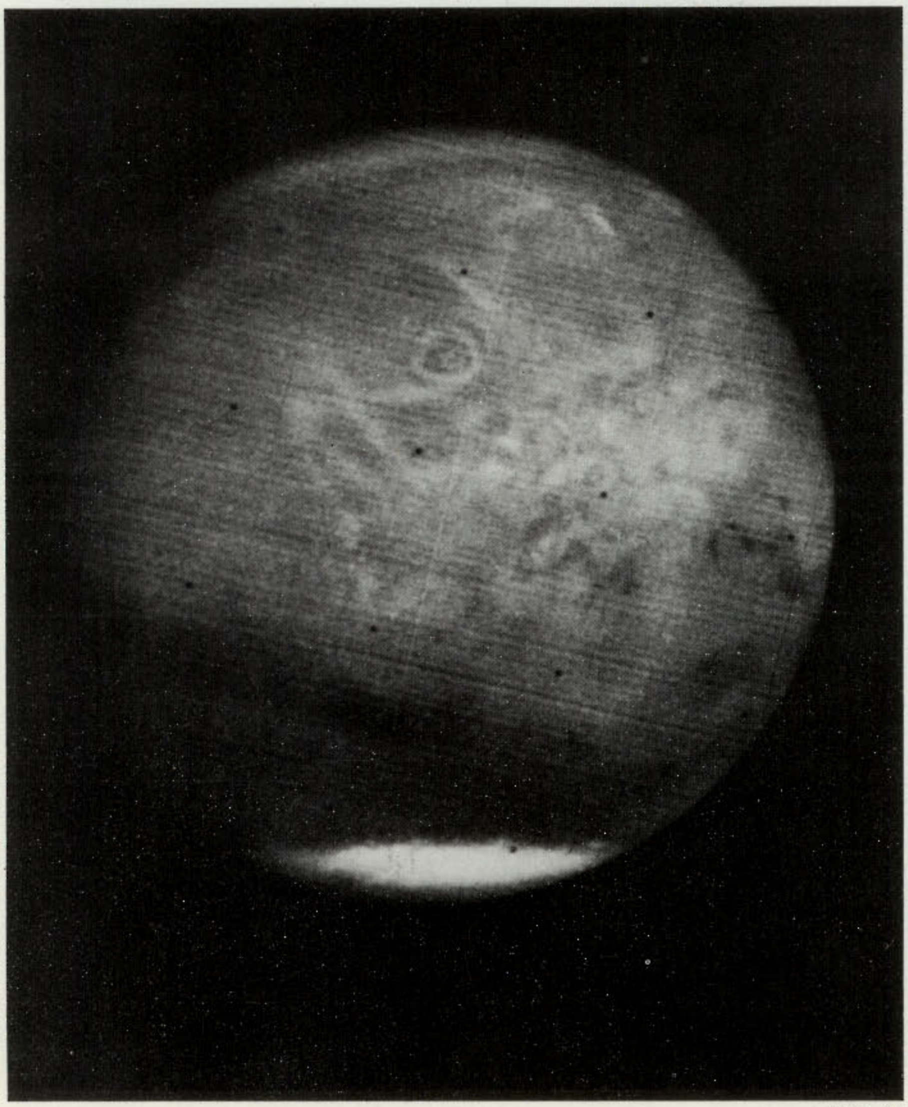


Plate 34

Plate 34 Mars photographed by Mariner 7 in August 1969. The south polar cap is at the bottom of the picture, bright ring-shaped object is the giant volcano Olympus Mons

Plate 35 A Martian channel in the central highlands. Many tributaries and a highly sinuous course characterise this type of channel

Plate 36 A great mass of chaotic terrain with a channel that flows into the northern lowland

Plate 37 A Martian sand dune field that is about 50 km across

Plate 38 The great equatorial fault valley with its diagonal subsidiary valleys. The valley is about 75 km across and 6 km deep

Plate 35

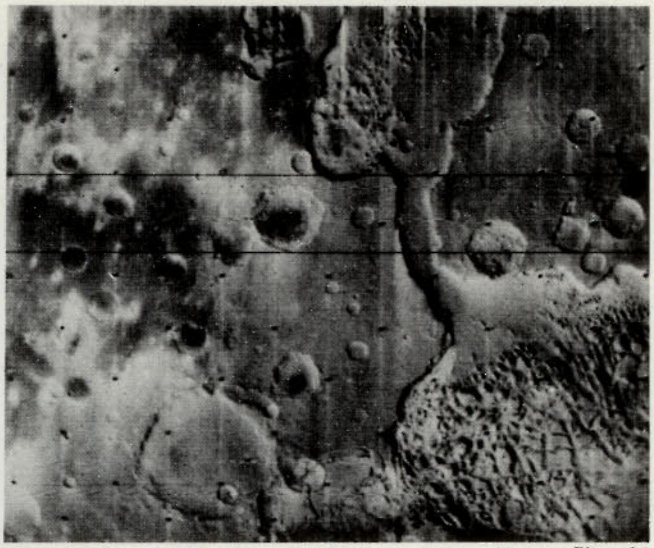


Plate 36

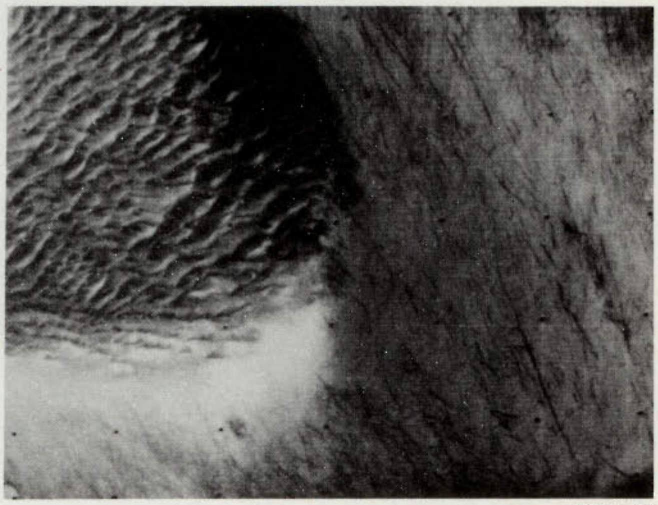


Plate 37

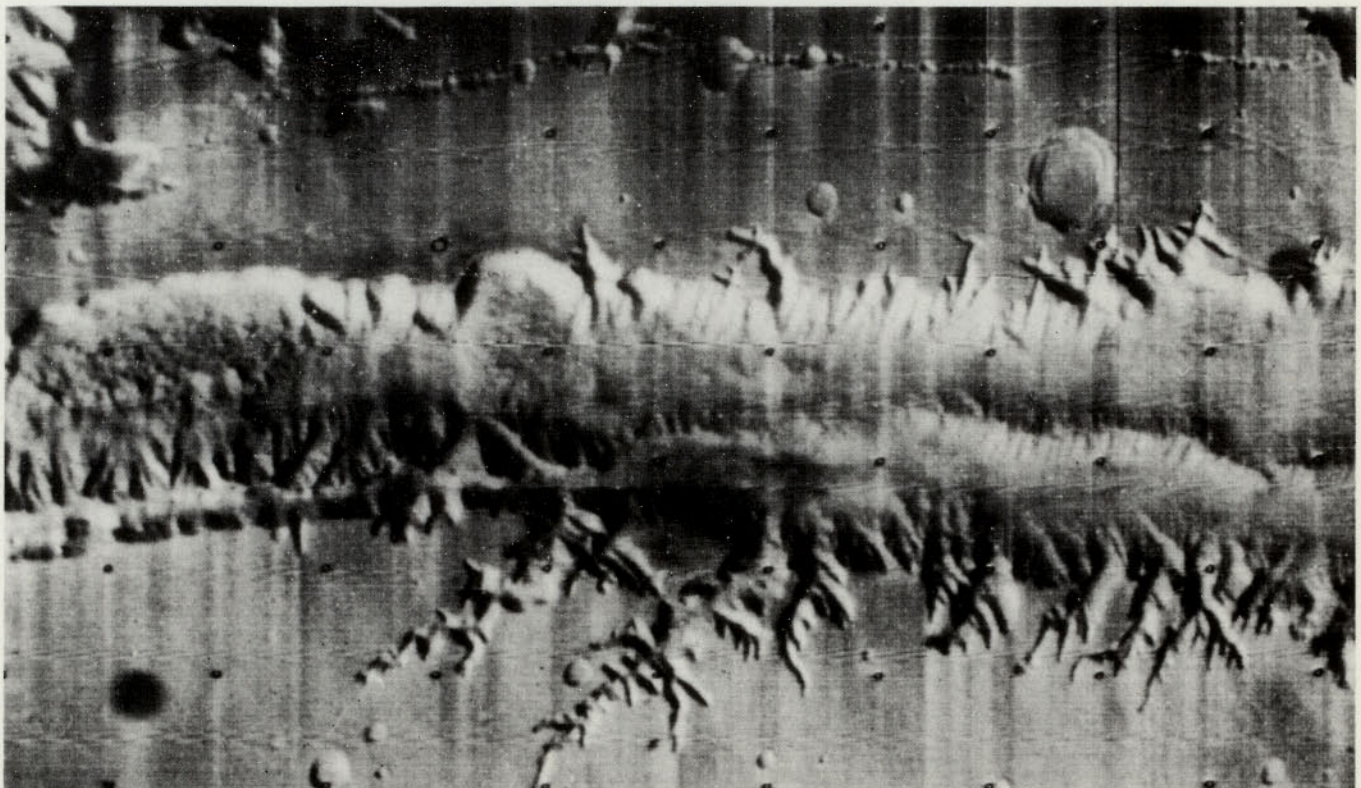


Plate 38

Plate 39 Photograph taken late in the Mariner 9 mission of the north polar ice cap and the dark ring around the cap. High-resolution pictures show the "etch pits" lie in the dark ring

Plate 40 Photograph of layered deposits near the Martian south pole. The closed depressions are the so-called "etch pits" eroded by the wind

Plate 41 Map of Mars compiled from about 1500 Mariner 9 pictures at a scale of one to fifty million. The bright and dark markings are derived from Earth-based telescopic photographs of the Planetary Patrol, Lowell Observatory. (Redrawn from US Geological Survey 1973 map)

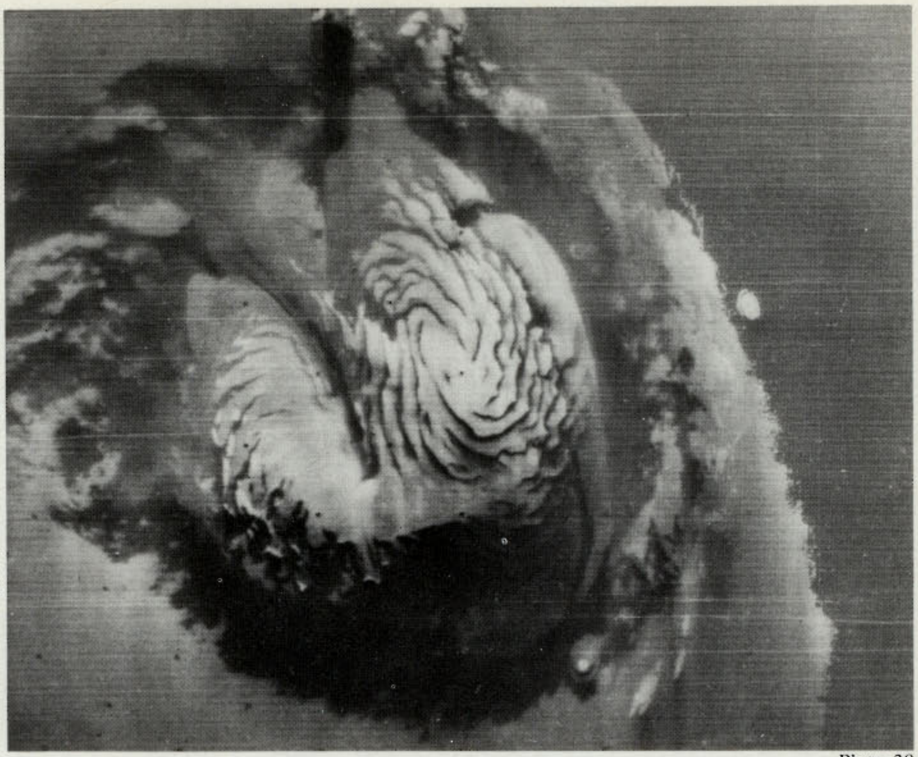


Plate 39

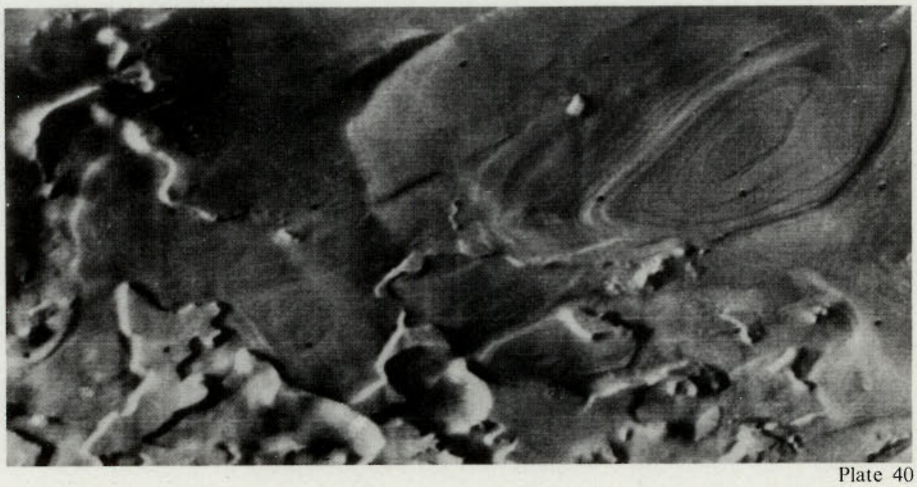


Plate 40

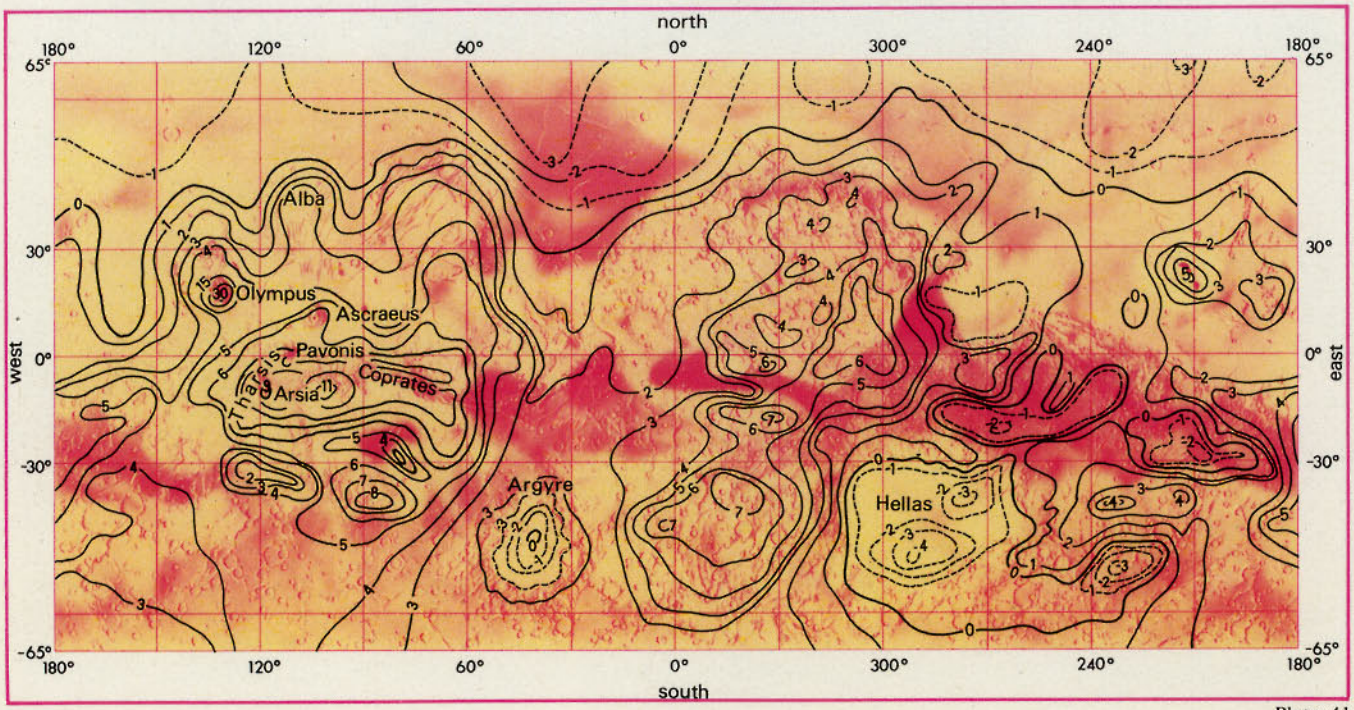


Plate 41

MARS

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HAROLD MASURSKY

Recent USA and USSR missions to Mars have recorded evidence for fundamental planetological processes and history and point the way to future missions. The exploration of Mars is at a particularly exciting stage now, comparable to that of the Moon after early photographic reconnaissance but before soft unmanned and manned landings, and before the return of samples. The information on hand about Mars is enough to encourage hypotheses, some of which will be checked in the near future by soft landing spacecraft due to arrive at Mars in July, 1976.

The USA had successful Mariner flybys in 1964 and 1969 and the USSR had successful orbiters and attempted soft landings in the period between 1971 and 1974. The bulk of our information comes from the successful Mariner 9 spacecraft that was inserted into Mars orbit in mid-November 1971 and continued to operate until mid-October 1972, sending back some 52 billion data bits including more than 7000 pictures.

Study of the pictures — including computation of mountain heights by stereoscopic means and by occultation measurements, as well as atmospheric pressure measurements by the infrared and ultraviolet spectrometers, and ground-based radar measurements — has resulted in the compilation of many topographic and geologic maps. There now exist planet-wide maps at scales of one to fifty million and one to twenty-five million, and thirty individual sheets covering the planet at scales of one to five million. Geological and terrain studies within special areas, completed at scales of one to one million and one to 250 000, will help to select candidate landing sites for American and Soviet spacecraft.

DISTINCTIVE HEMISPHERES

The most notable observation, perhaps, is the non-hydrostatic-equilibrium shape of the planet. It is pear-shaped; the southern hemisphere stands more than three kilometres above the nominal mean radius and is heavily cratered, indicating an ancient age for this part of the planet's surface. The northern hemisphere is low and smooth; the sparse density of craters indicates a youthful age. Many lobate scarps resemble flow fronts and indicate a possible basaltic composition for the lavas — an idea which is reinforced by the presence of mounds with craters on top, similar in appearance to terrestrial and lunar basaltic shield volcanoes. The lowest area lies in a broad belt centred near 65° north; from this belt elevations increase toward the north polar region which has a nominal mean Mars radius.

Several large multi-ringed impact basins lie in the southern highlands. The Hellas and Argyre basins are the largest; Hellas is nearly twice the size of the Imbrium basin on the Moon. Many smaller craters lie on a surface that looks much like the ancient southern highlands of the Moon.

The four largest volcanic structures lie near the equator; they are Olympus Mons, Ascreus Mons, Pavonis Mons, and Arsia Mons. The first rises about 27 km above the basin floor and is 500 km in diameter making it the largest volcano so far recognised in the solar system. Its shield-like shape, complex summit caldera, and the digitate flows on its flanks indicate a basaltic composition. The other three volcanoes are aligned along the edge of the 11 km high Tharsis plateau and reach the same elevation of approximately 27 to 29 km above the mean Mars radius.

Farther north, near Alba, is another volcanic centre. This volcanic area is more than 400 km in diameter but only a few km in height. It is flat topped with central calderas and is outlined by curved to semicircular sets of faults. Alba resembles terrestrial ring dike complexes,

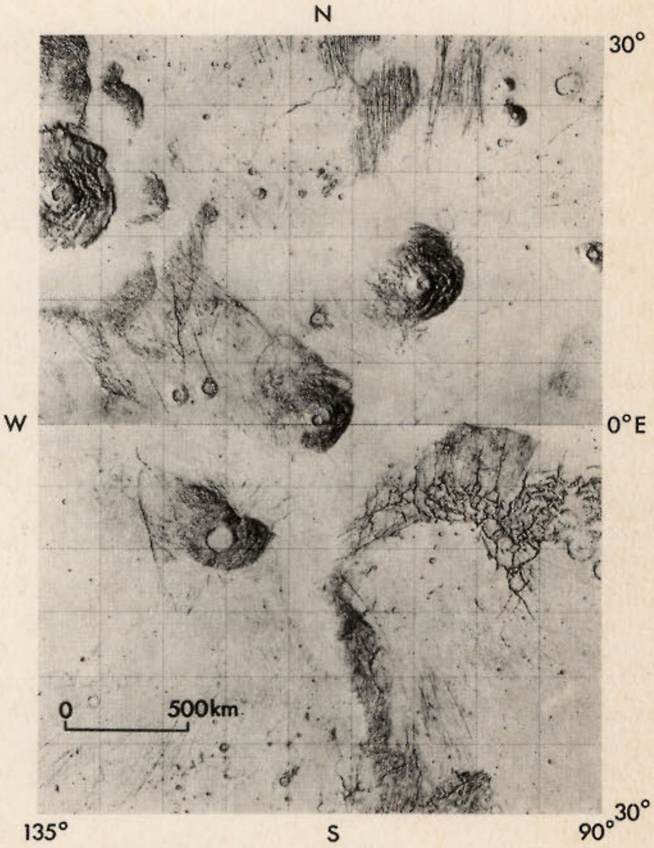

Figure 1 Map of the four largest volcanoes on Mars and western end of the great rift valley. Olympus Mons in the northwest corner of the map is about 29 km high. The map is a composite of two maps originally compiled at a scale of one to five million

which are volcanic centres characterised by highly varied and chemically differentiated rocks. Several superimposed craters indicate an intermediate age for the Alba complex in contrast to the large shield volcanoes that are, based on crater counts, very young. In the southern uplands other large volcanic centres are present, but they are degraded, heavily cratered, and very ancient. Comparison of their crater densities with lunar crater counts indicates that the older volcanic centres may be more than 3·5 billion years old, assuming similar rates of impact flux for the two planets. This great age indicates that volcanic activity on Mars started far back in time.

Eastward from the big volcanoes, the high plateau is segmented by a great rift zone that extends for 5000 km; in places it is 75 km wide and 6 km deep. The earliest

faults of this system are heavily eroded but the youngest faults cut the almost uncratered plains deposits and therefore are very young. This later faulting probably is associated with the uplift of the Tharsis plateau to as much as 11 km above mean Mars level.

Numerous meandering sinuous valleys that originate in great masses of collapsed rocks called chaotic terrain extend northward from the equatorial plateau. Other sinuous valleys in the uplands have many tributaries, and braided patterns as well as bars on their floors. Many other networks of small channels occur on all slopes in the equatorial region. They range from thoroughly degraded and densely cratered channels to fresh-appearing, uncratered ones, indicating a wide range in ages. All of these types of channels appear to have been formed by water flowing on the surface. As water cannot exist in the glacial environment that now prevails on Mars, vastly different climates are implied for the past. One hypothesis is that in former times the atmosphere was warmer and denser than at present. The ice caps and subsurface permafrost would have melted providing atmospheric moisture; rains would have fallen and water would have flowed on the surface. These interglacial periods must have occurred many times in the past to account for the widely different ages of channels. Their duration must have been short, however, because the erosional process was not able to destroy the pre-existing craters.

Figure 2 The flank of the great volcano Olympus Mons showing the long thin lava flows and channels. These flows resemble the recent flows on the basaltic shield volcanoes of the Hawaiian and Galapagos Islands

The north and south polar caps were monitored by Mariner 9 during their seasonal retreat. The caps cover almost 55° of latitude at their greatest extent and recede to cover only about 5°. At their greatest extent they have the temperature of carbon dioxide ice but the residual caps are intermediate in temperature between carbon dioxide ice and water ice. The rapid rate of retreat of the caps during Martian spring indicates that the outer parts of the caps are only a few cm in thickness. The polar regions are underlain by layered sediments that may be as much as six km thick, and consist of hundreds of thin parallel layers. Surrounding the layered deposits are many closed depressions that probably are formed by wind scour of plains materials. The circum-polar belt has been described as "etch-pitted" terrain. Sublimating ice may also have played a role in the formation of this terrain. Outside this region are the so-called riffles, sand dunes that are part of a wind-laid mantle of debris that thins toward the equator. The equatorial region is deeply scoured by the wind leaving grooves and hills having characteristic shapes and orientations.

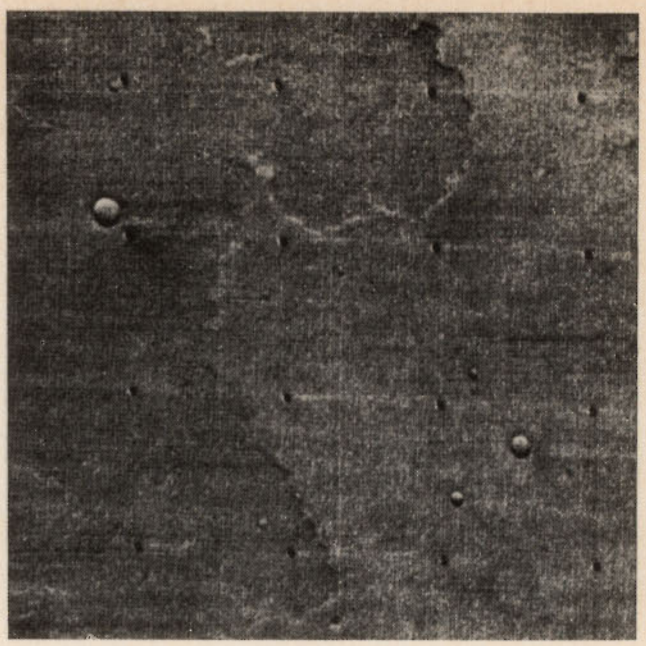

Figure 3 A lobate lava flowfront in the Martian northern lowlands

An aeolian erosion-deposition cycle has been detected. Wind transports debris from the equatorial region to the polar regions where it is deposited to form layered deposits. The same material is then re-eroded and transported equatorward to form the mantled terrain. This cycle seems to go far back in Mars time. Changes of light and dark spots seen in ground-based and spacecraft photographs probably are the manifestations of its present activity.

Mars appears to be a dynamic planet where impact, volcanism, tectonism, fluvial processes, and wind erosion and deposition all played important roles. The greatest problem lies in accounting for the topographical dichotomy — one hemisphere is low and young, the other high and old. Does the present surface of Mars resemble the Earth when "Pangea", the universal continent, existed before it was broken up by continental drift? Why are the Mars continental highlands restricted to one hemisphere? Was it by mantle convection? Can we learn about the early stages of the Earth's history by continued study of Mars?

Further exploration of Mars probably holds a high place in the future space programmes of both the United States and the Soviet Union. We can look forward to fundamental advances in our understanding of the evolution of all the terrestrial planets by this exploration.

WEATHER ON THE INNER PLANETS

RICHARD GOODY

Meteorology has advanced unevenly and by different paths in different eras: initially because of increased understanding of physical fundamentals; then through the development of novel synoptic techniques in the 1920s and 1930s; and latterly as the result of the introduction of new technologies, for example, the radio and the Earth satellite. Another rapid advance is imminent, on this occasion in our understanding of fundamentals—an unpredicted but important by-product of the last decade of space research.

A few years ago, we had data only for the Earth; now we have the three atmospheres of Venus, Mars and Earth to compare and contrast. Studies of a single, complex system are often unwittingly constrained by an acceptance of what is observed as "natural" and even "obvious" so that questioning is dulled and scientific enquiry suffers.

The most important consequences of our new understanding of fundamentals will be for climatology and for long-range weather forecasting. As we come to consider time scales longer than those of the normal two- or three-day weather forecasts, more of the external constraints upon the atmosphere become important. The existence of three different sets of constraints both stimulates new ideas and provides objective tests for theories.

Let us start with a deceptively simple question. Radio emission from the surface of Venus and infrared thermal emission from the cloud tops both show an equator-to-pole temperature difference less than 2 per cent of the mean temperature. For Earth the difference is about 15 per cent; while for Mars the difference is 40 per cent—and it might be more but for the ameliorating effect of the carbon dioxide polar caps. If the atmospheric temperature were controlled solely by the input of solar radiation and the emission of thermal radiation (the radiative balance) the equator would be hot and the poles cold: for zero inclination of the rotation axis the theoretical polar temperature would be zero and the equator-to-pole contrast would be 100 per cent of the mean. What characteristics of the three planets therefore give rise to the observed relationships? Until data on Mars and Venus became available, this fundamental question was not asked—even for Earth—let alone answered.

The effect of a fluid on a planet (liquid or gaseous) is to transfer heat by a variety of convective processes from the equator to the poles. If the fluid convection is the dominant process we may expect small (but non-zero) temperature differences over the surface of the planet. If horizontal mixing is not strong, however, the atmosphere must achieve a local balance between incoming and outgoing radiation, with very large temperature contrasts between equator and pole (see Figure 1). Both radiative and dynamical processes must be present on a planet: the former is the fundamental drive and the latter is an inevitable response. The magnitude of the temperature contrast is a consequence of a conflict between these two modes of heat transfer. Their relative importance can be measured in terms of thermal relaxation times for the two processes; the more rapid process, that with the shorter relaxation time, will dominate.

Table 1 shows some relevant data for the three planets. On a rotating body circulation is controlled to greater or less extent by the Coriolis force. The dynamical relaxation, or response, time (column 10) is approximately equal to the inverse of a Coriolis parameter (equal to twice the angular velocity times the cosine of the co-latitude, see column 6) for rapidly rotating planets, such as Mars and Earth; and to the time for a sound wave to encircle the globe, for a slowly rotating planet such as Venus. It is therefore determined by the gross properties of a planet, and is largely independent of the nature and amount of the atmosphere itself.

On the other hand, the radiative response time is that time required for solar energy to raise the atmospheric temperature from zero to its present value and is proportional to the mass of the atmosphere, which is in turn proportional to the surface pressure. This latter quantity varies over a very wide range. Venus, with a surface pressure of 90 atmospheres, has a surface density nearly one tenth that of water. Mars, however, has a surface pressure of only 6×10^{-2} atmospheres, equal to the pressure on Earth at an altitude of 20 km.

Since the shorter time constant prevails in a competitive situation, we can see (Table 1, columns 9, 10) that the effect of dynamical transport is strong on all three planets; it is strongest on Venus and least strong on Mars, while Earth occupies an intermediate position, explaining, in a general way, the relative magnitudes of the temperature contrasts on the three planets.

If we compare the radiative relaxation time (column 9) with the length of each planet's day (column 8) we can form a first estimate as to whether the atmospheric temperature can change significantly during a day. If the relaxation time is much longer than a day the change of temperature through a day will be slight, and *vice versa*. The former statement applies to both Earth and Venus. Although the Venus day is much longer

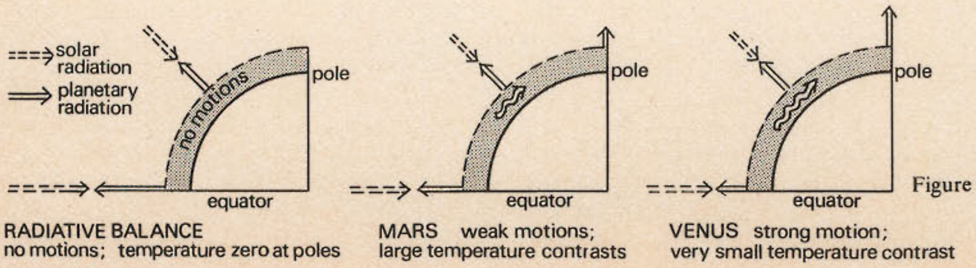

Figure 1 Radiative and dynamical heat fluxes

TABLE 1 COMPARATIVE METEOROLOGICAL PARAMETERS FOR THE INNER PLANETS

planet	1 surface pressure (atmos)	2 average surface temp. (K)	3 atmospheric constituents* major	minor	4 cloud amount (per cent)	5 surface conditions	6 30° Coriolis parameter (per second)	7 topography scale height	8 length of day (seconds)	9 relaxation times radiative (seconds)	10 dynamical (seconds)	11 adiabatic lapse rate (K/cm)
Venus	90	750	CO_2	HC1, HF, CO, H_2O	100	chemical equilibrium	6×10^{-7}	0·2	$1{\cdot}02 \times 10^7$	1×10^9	3×10^4	$1{\cdot}01 \times 10^{-4}$
Earth	1	300	N_2 O_2 A	CC_2, H_2O, O_2, etc	50	liquid	7×10^{-5}	0·3	$8{\cdot}6 \times 10^4$	1×10^7	3×10^3	$9{\cdot}7 \times 10^{-5}$
Mars	6×10^{-2}	230	CO_2	O_2, H_2O, CO	5	dusty	7×10^{-5}	1·0	$8{\cdot}9 \times 10^4$	2×10^5	5×10^3	$4{\cdot}5 \times 10^{-5}$

* Established constituents only. For example, N_2 may be a major constituent on both Mars and Venus.

than Earth's the radiative relaxation time is also longer because of the greater atmospheric mass. The two effects almost compensate. We do not therefore expect either Earth or Venus to exhibit large diurnal changes in the troposphere (the lower convective layer of the atmosphere largely responsible for weather): this is what we observe on Earth. Such small changes as do take place, however, couple around the globe to form tidal modes which, under the appropriate circumstances, transmit oscillatory energy upwards with steadily increasing amplitude.

A unique opportunity to study these atmospheric tides is offered by Mars, whose radiative relaxation time is only twice the length of the day. We can therefore predict temperature oscillations in the troposphere even with a non-dynamical theory, and very large oscillations are observed. According to one set of calculations, in which no motions are included and heat transfer is by radiation and free-convection alone, most of the temperature variation is restricted to the lowest few kilometres: the diurnal change at 10 km is 6 K; near 30 km it is 3 K. Measurements from the Mariner 9 orbiter, shown in Figure 2, indicate 20 K or more at 10 km, and at least 10 K near 30 km.

At the present time, there is no complete theory of these large Martian tides. If thermal excitation, which dominates on Earth, proves to be inadequate there are

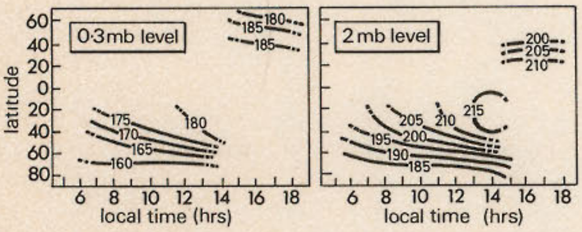

Figure 2 A preliminary reduction of Martian temperature (K) at two atmospheric levels (2 mb is approximately equivalent to 10·2 km and 0·3 mb to 28·3 km). The data were obtained from Mariner 9 by means of a scanning Michelson interferometer used as an infrared thermal probe

novel circumstances on Mars which must be considered. For example, the diurnal rise and fall of the convective layer which seems to occur there could, even in the absence of thermal effects, produce a tidal wind by mixing momentum periodically down to the planet's surface where it can be destroyed by friction. Another interesting possibility is the occurrence of motions, like the resonant oscillations called seiches observed in small seas, in the deep basins that characterise the Martian surface. Table 1, column 7, shows the approximate height contrast between continents and basins in terms of the equivalent depth of the atmosphere (scale height). In some respects the atmosphere of Mars may behave more like a series of interconnected oceans, with western boundary currents and other phenomena more familiar to the oceanographer than to the meteorologist.

A discussion of Martian dynamics can roam through a wide variety of fascinating topics, but we must also ask what Venus has to offer as a stimulant to further investigations of tidal theory. At least, it teaches us to have an open mind, for one of the results of periodic absorption of solar energy near the cloud tops is probably to produce a toroidal wind, rotating with the planet and around the same axis, but 60 times faster than the surface. The linear motion of the clouds is 100 m/s. Observational evidence establishing this extraordinary wind comes from doppler shifts of CO_2 lines.

The motions discussed in the previous section are global in character. In the case of Mars major weather phenomena will be associated with the tidal motions. Strong winds will blow from different quarters at different times of day throughout the troposphere (such diurnal behaviour is observed close to the Earth's surface in the form of sea breezes but this is a boundary phenomenon and not a planetary-scale tidal motion). As well as diurnal driving forces there are those associated with the general differences of heating between equator and poles. This effect is important for Mars, but for Earth and Venus it dominates the planetary meteorology.

The weather systems in the middle latitudes of Earth are a product of the global circulations. On a rapidly rotating planet, heated more at the equator than at the poles, Coriolis forces give rise to westerly winds aloft. If the equator-to-pole temperature gradient is large these strong zonal winds develop wave-like instabilities with which are associated high- and low-pressure weather systems (see Figure 3). The instabilities are more intense in winter than summer because the temperature contrast between equator and poles is greater at the winter solstice.

Let us consider how these ideas can be applied to Mars. The different composition and mass of the atmosphere are not important here. That very little water condensation takes place on Mars could be significant, but most important are the rotation rates and equator-to-pole differences of insolation. In the winter hemisphere the conditions are similar for Earth and Mars so that similar circumstances should prevail, and they probably do so. Some Mariner 9 photographs show a development of Martian clouds which is very similar to the development of a terrestrial cold front. There is little doubt that, in some respects at least, analogous weather processes occur on the two planets.

In the summer hemisphere the planets may differ. The axial tilt of both allows, at the solstice, slightly more

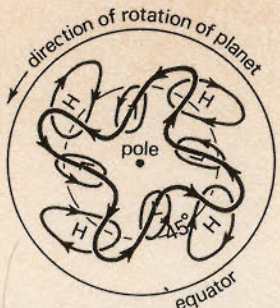

Figure 3 Unstable waves in the upper level westerlies (heavy line). The lower level cyclones (L) and anti-cyclones (H) associated with the waves are indicated by the thin lines

insolation in the summer polar regions than at the equator. Its relatively dense and cloudy atmosphere gives Earth a high reflectivity in the polar regions so that less solar radiation actually reaches the ground at the poles than the equator, even in midsummer. For the transparent Martian atmosphere the reverse gradient may exhibit itself. The prevailing winds are then *easterly;* they will also be light; the usual planetary waves should be absent, and there should be little in the way of weather. The dominant wind systems should then be the tidal winds, discussed in the previous section.

Figure 4 shows a schematic representation of these ideas. The two wind systems must be combined, and the way in which they do so will be influenced, among other factors, by the large topographic contrasts which exist on Mars. This difference between the two planets may

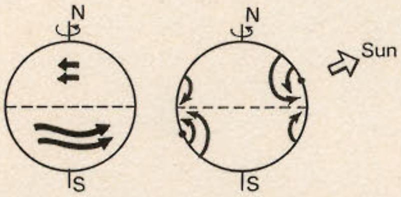

Figure 4 Zonal (left) and tidal (right) winds. The zonal winds blow predominantly eastward or westward. They may be stable in the summer hemisphere but are certainly unstable in the winter hemisphere (cf Figures 3, 4). The tidal winds are schematic. The pattern is fixed with respect to the Sun, while the Earth rotates underneath

eventually turn out to be the most instructive of all from the theoretical point of view.

The slow rotation of Venus will give rise to a very different circulation. Figure 5 shows one attempt to describe a possible deep circulation beneath the cloud tops (the clouds lie about 60 km above the surface and the pressure there is about 100 mb). The purpose of this investigation was to understand whether the compression in the deep flow could create an adiabatic gradient (Table 1, column 11) and thus be responsible for the high temperature (750 K) observed at the

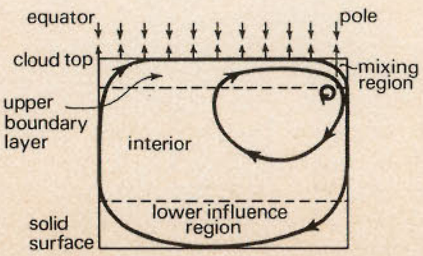

Figure 5 A heuristic model of the deep circulation of the Venus atmosphere

planet's surface. The question is unresolved, but such investigations are instructive also for Earth because the tropical winds exhibit some features of a non-rotating system. The northern component of the north-easterly trade winds forms the north-to-south component of a circulation which is completed by a rising current in tropical regions and a south-to-north branch aloft. This circulation, known after its discoverer, Hadley, might have some similarities to the deep circulation of the Venus atmosphere.

The recent Mariner 10 spacecraft to Mercury flew by Venus and recorded ultraviolet images of the cloud forms at a height of about 60 km above the surface. In (Plate 10, p 21) the poles are covered by light caps of cloud (upper left and lower right) and the equator crosses the centre of the planet, tilting from lower left to upper right. The spectacular feature of this picture is the spiraling motion illustrated by the cloud streaks which stretch from equatorial regions. The poleward component of these motions is compatible with the Hadley cell discussed above. There is, however, also a strong east-west motion of about 100 m/s, not explained by such a simple mechanism.

The existence of this so-called "4-day circulation" (the time for one equatorial revolution of the clouds) had already been demonstrated by ground-based observations leading to a great deal of theoretical interest in the question of generating such a high angular momentum on a slowly rotating planet. Plausible explanations have been given upon unusual mechanisms connected with the diurnal periodicity of heating at the cloud tops and differential rates of diffusion of heat and momentum. Since no similar phenomena appear to exist on Earth we will only learn more about this aspect of planetary circulations from space probes to Venus.

We have seen how terrestrial weather is associated with instabilities in the global circulation. The resulting motions generate cloud systems by ascent of moist air, and these clouds have important but secondary effects upon the motions.

The most violent storms—hurricanes (typhoons) and tornadoes—do not, however, appear out of thin air. The energy source for these violent storms is associated with clouds and condensation, while their form and detailed mechanisms involve the angular momentum of the ambient air.

We cannot expect to find close analogies to these events on Venus because of the planet's very slow rotation rate. Venus is interesting because the cloud cover is so complete, unlike Earth for which the co-existence of rising and descending currents leads to some 50 per cent cloud cover (Table 1, column 4). We are forced to conclude that the two planets differ in that only one has the physical conditions necessary to produce heavy precipitation of condensible constituents. The Venus cloud (which may consist of sulphuric acid droplets) is probably more similar to an urban smog than to the dense water clouds in a terrestrial storm. Ideas as to the thermodynamics of this ubiquitous cloud layer have been developed which may be applicable to special problems of stratus cloud in the arctic and in inland California valleys. However, it is to Mars that we must look for any inspiration about such important topics as the nature of a hurricane.

The Martian "great dust storm" is a spectacular phenomenon for which there appears to be an explanation analogous to that of the initial stages of a hurricane. At rare intervals, a bright yellow core of suspended dust is observed to form over one of the raised "continents" near to the southern tropic, at the time of

the southern solstice. The storm goes through a life cycle in which it begins to expand after two weeks and eventually obscures almost the entire planet after five or six weeks; thereafter it takes 10 to 25 weeks to clear completely.

By coincidence, the US Mariner 9 and the Soviet Mars probe both arrived at Mars in 1971 at the start of a great dust storm. Early views from Mariner 9 revealed only the huge volcanoes showing through a dense haze. Figure 6 shows a schematic representation of the mature phase of the storm as visualised in a theory, based upon the early phases of a hurricane, which can explain most aspects of the observed storm. The important distinction between the two phenomena lies in the thermal drive; the similarity lies in the mechanics for intensely rotating cyclonic storms. For Earth, buoyancy is created by condensation and precipitation of large amounts of water, evaporated from the warm tropical oceans. For Mars, the dust itself provides the source of energy. Similar amounts of solar energy can be absorbed in a haze on the two planets, but the Martian atmosphere has less than 2 per cent of the mass of the terrestrial atmosphere and the effect upon temperature and buoyancy is greater in inverse proportion. Heating rates as large as 25 K/day can exist when dust is lifted off the Martian surface and into the atmosphere. Through the mechanism of the hurricane, this heating produces high wind speeds which raise more dust and give rise to additional heating. To start the sequence requires that a sufficient amount of dust be raised over a sufficiently large area by some other mechanism: the small whirlpools known as dust devils may fulfil this purpose.

Even the most far-sighted national weather service is unlikely to see direct benefits, as regards its year-to-year mission, from the planetary research which I have described. Nevertheless, there are few meteorologists who would not recognise the probable future impact upon meteorological theories of the new ideas arising from our knowledge of Mars and Venus. Not enough reason, one might argue, to justify the great expense of space research. This is a legitimate matter for debate, but among the facts to be considered are the foregoing evidence and the parallel cases that can be made in tectonophysics, aeronomy and fundamental biology, as well as the possibility of establishing facts to replace speculation about the origin of life and the origin of the solar system. The US space programme is seeking new objectives and rationales. If in no other way, this rationale could be provided by a systematic unmanned programme of exploration of the solar system.

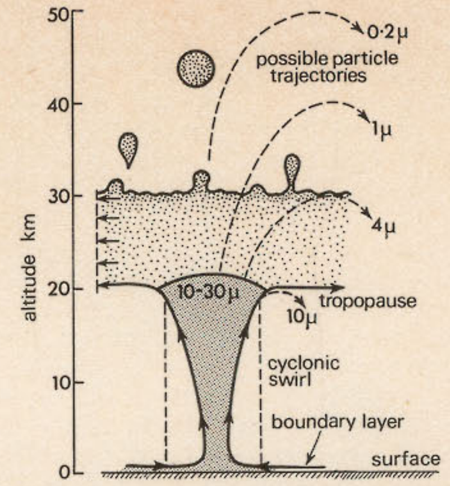

Figure 6 A schematic representation of a great dust storm in its mature phase. The flow below 20 km is cyclonic. The boundary layer pumps dust inward to a central column where it is heated by absorption of solar radiation. The column and its rotating flow are disrupted by the change in temperature gradient at the tropopause. Above the tropopause the flow spreads sideways to obscure the entire planet. Broken lines show how particles of different diameters can rise to different heights

JUPITER

♃

GARRY HUNT

Beyond the orbit of Mars and the asteroid belt lies Jupiter, the largest planet in the solar system surrounded by its 13 satellites. Two of its members, Ganymede and Callisto, are larger than our Moon. Jupiter is a huge planetary body with a radius more than 11 times that of the Earth which spins rapidly on its axis so that its day is only approximately 10 hours. It has fascinated visual astronomers since the time of Homer, and has an appearance of alternating light and dark bands of varying colours; greys, browns, purples, yellows, blues and reds which appear to change in only a few planetary revolutions, with the Great Red Spot in the southern hemisphere.

The mass of Jupiter is more than $2\frac{1}{2}$ times that of all the other planets added together and 300 times greater than the mass of the Earth. In spite of its size, Jupiter has a surprisingly low density of only 1·3 g per cu. cm, compared with a typical value of 5 g per cu. cm for the density of rocky material of the terrestrial planets. The low density is a characteristic of all the major planets in the outer portion of our solar system. The difference in density suggest that the major planets, like the stars, are entirely composed of light elements — hydrogen, helium, carbon, nitrogen — while silicates, iron and nickel chiefly constitute the cores of the inner planets. Since hydrogen and helium are thought to be the principal constituents of the primordial solar nebula, Jupiter may hold the key to the formation of the solar system.

Radio astronomers have made discoveries which further emphasise the importance of Jupiter in our solar system. They discovered that Jupiter possesses a strong magnetic field and belts of trapped radiation. Does the field originate from the dynamo action of a core of hydrogen and helium (if it is present) in liquid metallic phase? At the present time the Earth is the only other planet known to be magnetic and its field originates from dynamo action within an iron core. Jupiter also creates its own radio signals. Sporadically, the planet emits great electromagnetic bursts equivalent in energy to those of thermonuclear devices. The satellite Io modulates these bursts. Another kind of Jovian emission is the synchrotron radiation caused by the acceleration of electrons along the magnetic field lines.

To understand the origin and evolution of the solar system requires a detailed study of the major planets situated beyond the asteroid belt. Collectively these possess 99 per cent of the total mass, and more than 90 per cent of the angular momentum of the solar system. The exploration of Jupiter is the first step in such a study. Pioneer 10, launched on 2 March 1972 to explore the potentially dangerous Jovian environment for future space missions, reached its point of closest approach — 2·86 Jupiter radii (R_J) — at 02.25.19 GMT on 4 December 1973 to record a further major accomplishment in NASA's exciting and scientifically rewarding planetary programme.

Pioneer 10 first encountered the Jovian environment on the 26 November 1973 when, at 108 R_J, it crossed the bow shock wave which is the boundary between the interplanetary magnetic field and the planet's magnetosphere. A day later, the spacecraft traversed the magnetopause at 96 R_J and entered the planet's extensive magnetosphere. The Earth's magnetosphere, which extends to 13 Earth radii (R_E) (just greater than 1 R_J) would seem quite small in comparison. Indeed, if the Jovian magnetosphere were visible from the Earth, it would occupy as much sky as the Sun!

The observations made with the vector helium magnetometer on board Pioneer 10 have provided information on the overall shape of the Jovian magnetic field. Assuming the field to be purely dipole, that is to say, one having the same shape as a bar magnet, the initial field strength at the surface of the planet was calculated to be 20 gauss. Unexpectedly, however, subsequent measurements made closer to the planet showed that the magnetic field was more complicated than the original suggestion and considerably more complex than the Earth's field.

The Jovian field appears to form two quite distinct regions: a dipole of strength 4 gauss, which is eight times the strength of the Earth's field, extending to 20 R_J; and a non-dipole field occupying the remainder of the magnetosphere (Figure 1). The Jovian dipole is oriented opposite to the Earth so that the magnetic field points south at the equator. The magnetic axis is inclined at 11° to the planetary spin axis. The dipole is displaced from the centre of Jupiter by 0·1 R_J north of the equatorial plane. While the dipole tilt and longitude of the pole are in good agreement with the values derived from Earth-based radio astronomy observations, the magnetic moment and offset derived from the Pioneer 10 measurements represent a significant gain in our knowledge of the Jovian magnetic field.

The observed field in the outer region (beyond 20 R_J) is much more confined to the Jovian equatorial plane and greater in magnitude than that produced by the dipole field. During Pioneer 10's outward path, at 30 R_J the observed field magnitude departed significantly from that predicted by the dipole; while at 50 R_J the observed field is nearly constant at approximately 10 gauss. This outer region may be represented by an eastward current sheet forming an annulus with Jupiter at the centre. The current sheet is warped so that it is above the equator on one side and below it on the other; it rotates with the planet, more or less like a rigid body, causing an apparent up and down motion which Pioneer 10 periodically crossed sheet (Plate 44).

Jupiter's radiation belts, regions where protons and high-energy electrons are trapped by the planet's magnetic field, appear to be 10 000 times more intense than the Earth's Van Allen belts. The spacecraft first detected energetic particles with energies greater than tens of keV at distances as far as 300 R_J from the planet, though the most intense part of these belts lies within 20 R_J. During its passage through the radiation belts the spacecraft received an integrated dose of 200 000 rads from electrons and 50 000 rads from protons of energy above 30 MeV. For man, a whole body dose of 500 rads is lethal!

The Pioneer 10 observations suggest that only in the central portion of the Jovian magnetic field (closer than

IO: THE SMALLEST KNOWN BODY WITH AN ATMOSPHERE

Jupiter possesses a rich satellite system of 13 moons and the Pioneer 10 mission has provided the first opportunity to inspect some of them at close range. From the radio tracking data of Pioneer 10, the densities of the four large satellites appear to be: Io 3·48; Europa 3·07; Ganymede 1·94; and Callisto 1·65 g per cu. cm. In general, bodies with density larger then 3·0 are probably rocky, silicate structures while those of density less than 2·0 may have a large percentage of ice. Io would now seem to be an object of the type found in the inner solar system. Furthermore, the density gradient in the satellites decreases outward from Jupiter. This is just like the properties of the planets in our solar system as we move away from the Sun and reinforces Galileo's original concept of the Jovian system. This property of Jupiter and the Galilean satellites may indeed have important cosmogonic implications.

Io is an anomaly not only among the Galilean satellites, but among all the bodies in the solar system. Its size and shape are comparable to the Earth's Moon but its interaction with the Jovian environment is very much greater than the Moon's interaction with the Earth's magnetotail. The satellite has a 42-hour orbital period around Jupiter and its orbital position is known to influence the planet's decametric radio bursts.

The Pioneer 10 S-band occultation experiment found that Io has an ionosphere extending some 700 km above the surface on the day side. The diminished night-side ionosphere indicates that this region is produced by solar radiation on the day side, then gradually decays during the 21-hour Io night. The satellite also has a tenuous atmosphere with a surface pressure of between 10^{-8} and 10^{-10} bar. Io is therefore the smallest body known to possess an atmosphere.

The presence of an atmosphere and ionosphere had been predicted before the spacecraft encounter. Several astronomers have reported an increase in brightness sometimes lasting 15 minutes upon the re-emergence of the satellite from Jupiter's shadow, while other observers have failed to detect any change in brightness. It is possible the presence of ammonia on the surface of the satellite and in the atmosphere, which responds to seasonal changes, may explain the intermittent post-eclipse brightenings. A further prediction followed the detection of sodium D emission from the vicinity of the satellite.

Around Jupiter is an extensive cloud of atomic hydrogen similar to the cloud around Titan, the satellite of Saturn. The Jupiter torus is not complete, however, but seems to extend only for 60° on either side of Io. These clouds are formed by atoms which can escape from the satellite but not from the influence of the planet owing to its large gravitational field. Consequently the atoms are bound in closed orbits until lost by ionisation or recapture, and tend to produce a toroidal cloud whose density is determined by the ionisation losses. The cloud around Jupiter occurs at the orbit of Io with a brightness of 10 J Rayleighs. It is probably less than 2R_J in thickness. The preliminary estimate of the cloud content is approximately 2 × 10^{33} atoms, with a mean lifetime of 55 hours. This is slightly longer than Io's orbital period so that the torus may be a constantly replenished permanent feature around Jupiter.

Is Io the source of these atoms? That is certainly possible; the satellite probably produces a sodium cloud from the sputtering of its surface by Jovian magnetospheric particles. This mechanism would also be a source of neutral hydrogen from the sputtering of ices and previously absorbed protons.

20 R_J) does the magnetosphere behave in a manner similar to that of the Earth. In the region beyond 20 R_J extending to the magnetopause boundary, both electrons and protons are highly concentrated near the magnetic equator, especially on the dawn side of the planet.

The Jovian radiation belts present themselves as a formidable hazard for any spacecraft. Indeed, at closest approach the flux intensities were so large that the electrical instruments on board Pioneer 10 were about 95 per cent saturated; while the asteroid-meteoroid detector was seriously damaged by the radiation. Had the spacecraft been closer to Jupiter by as little as 0·5 R_J the mission would probably have failed.

How then, did Pioneer 10 manage to survive? Prior to the spacecraft encounter there was some speculation about the effect on the radiation belts of the Jovian moons Amalthea, Io, Europa and Ganymede. These four satellites all orbit inside the Jovian magnetosphere in the equatorial plane. This is a new and interesting problem for magnetospheric physics since our own Moon lies at approximately 60 R_E well *outside* the terrestrial magnetosphere. The University of California (San Diego) Trapped Radiation detector discovered a significant interaction between both Europa and Io and Jupiter's radiation belts. The particle sweeping effects of these satellites and their two neighbours as they interact with the corotating planetary magnetosphere may therefore have been of fundamental importance for the success of the mission. These are interesting results to consider for Saturn, which is similar to Jupiter in its physical and chemical properties, but so far appears to be non-magnetic. Does the presence of the rings around Saturn prevent the formation of radiation belts around the planet and even a weak magnetic field? We may know the answer to this intriguing question in 1979 when Pioneer 11 passes inside the rings.

One of the most intriguing discoveries of the Jovian environment which Pioneer 10 unveiled concerns bursts of relativistic electrons apparently ejected by Jupiter. These bursts were first detected more than six months before encounter and increased in magnitude as the spacecraft approached the planet. They are not solar particles since they come from the wrong direction, nor are they likely to be interstellar particles leaking into the solar system. Apparently they possess a periodicity of 10 hours coinciding in phase with variations inside the Jovian magnetosphere. Jupiter may be radiating waves of particles outward over a wide range of latitudes.

The occultation experiments on Pioneer 10 have detected a highly structured Jovian ionosphere extending over an altitude range of approximately 3000 km. Atmospheric dynamics may play an important role in determining this structure. The topside plasma temperature is of the order of 1000 K. The major constituent is probably H^+ ions. An understanding of Jupiter's ionosphere is important for explaining the curious Io-related phenomena which occur.

A "PRIMORDIAL" COMPOSITION?

Helium, the second most abundant element in the solar system, was positively identified for the first time in Jupiter's atmosphere by Pioneer 10's ultraviolet photometer. Jovoan helium cannot be detected from the Earth. Jupiter's atmosphere, we know, consists mainly of hydrogen, with smaller contributions of helium, ammonia, methane, and traces of deuterium, acetylene, ethane and phosphine. The Pioneer 10 data suggest a helium/hydrogen ratio of 0·18 approximately. This value, and the estimates for carbon and nitrogen abundances are close to the solar value suggesting that the planet has a composition similar to that of the primordial nebula. Therefore, in Jupiter and its satellites, we are observing planetary bodies whose evolution has probably been slow as a result of the low temperature in the outer solar system.

The infrared radiometer measured for the first time the temperature of the dark side of Jupiter which is inaccessible from the Earth. It found no significant difference between the temperatures of the sunlit and dark sides. Such a result is to be expected for a planetary atmosphere whose characteristics are dynamically — rather than thermally — controlled. The lower atmosphere of Venus is another example of a dynamically controlled environment which shows a similar feature of no diurnal change in temperature. There is, however, an interesting difference in the rotation rates of these planets. Venus, about the size of the Earth, rotates on its axis in 117 days. Jupiter, whose radius is more than 11 times larger than the Earth, rotates in approximately 10 hours and exhibits a complicated differential rotation between the surface belts and zones. This rapid rotation also causes the planet to be markedly flattened at the poles.

The infrared radiometer also measured a brightness temperature of 128 K for Jupiter which, using a planetary albedo of 0·42, confirms that the planet emits more than twice the amount of energy it receives from the Sun. This is a highly significant result. The additional energy may be the result of an internal heat source produced by the conversion to potential energy of the gravitational contraction of the planet by as little as one mm per year. The extra energy would be transported from the interior to the "surface", through the atmosphere of the planet and out to space. Consequently the Jovian meteorology will be internally driven. This is quite unlike the meteorology of the terrestrial planets Earth, Venus and Mars whose atmospheres are in radiative balance and whose weather systems are driven by the Sun.

The visible appearance of Jupiter is a banded structure parallel to the equator of alternating light and dark bands of rapidly changing colours, with the Great Red Spot predominant in the planet's southern hemisphere. Since ammonia is a constituent of the Jovian atmosphere it will condense into a layer of cloud at some tropospheric level. Indeed we believe that ammonia cirrus clouds mark the top of ascending fluid which corresponds to the *bright zones*, while the regions of cool descending fluid are obscured by the haze and appear as *dark belts* (Plates 42 and 43). This structure is confirmed by Earth-based and Pioneer 10 infrared radiometers which find the belts warmer than the zones. Beneath the ammonia cloud we expect other cloud layers to form, although their structure and composition are at present unknown. However, we believe the effective emission temperature of the dark belts, at wavelengths where there is negligible atmospheric absorption, corresponds to the top of a dense cloud layer. The observations of Jupiter at visible and thermal infrared wavelengths therefore sample only the upper tropospheric levels of the planet's huge and dynamic atmosphere.

As well as clouds, aerosols formed from photochemical reactions of the atmospheric constituents may form at upper levels of the troposphere and stratosphere. These would modify the temperature structure and atmospheric motions of this region. Indeed, the radio occultation data suggests there may be a layer of aerosol

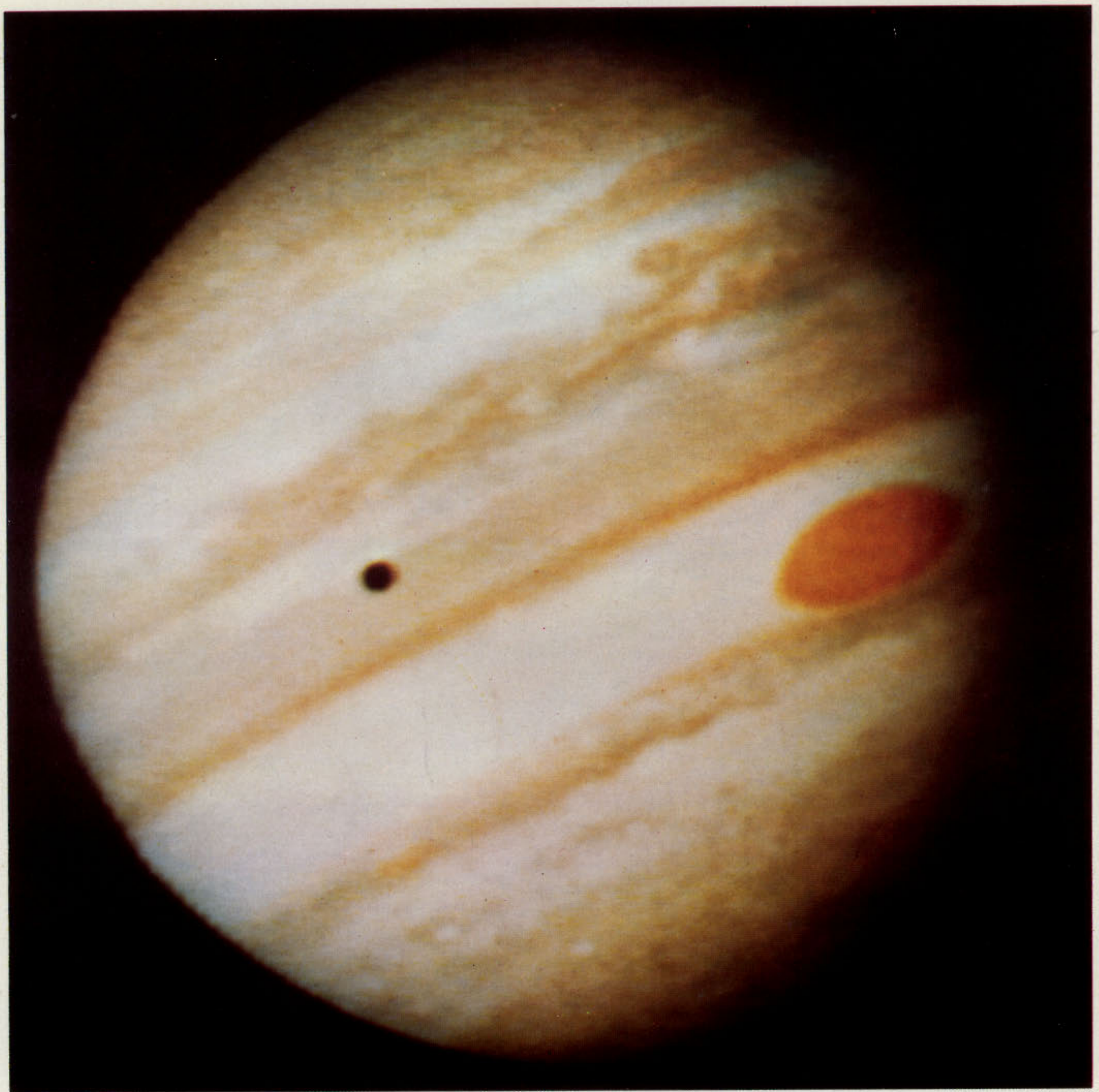

Plate 42

Plate 42 An image of Jupiter taken on 1 December 1973 when Pioneer 10 was 2 500 000 km from the giant planet. The dark spot is the shadow of Io

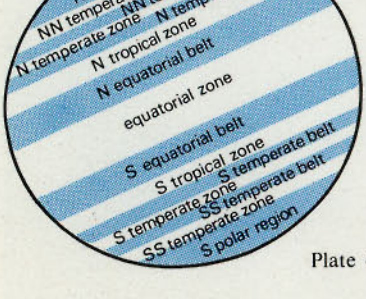

Plate 43

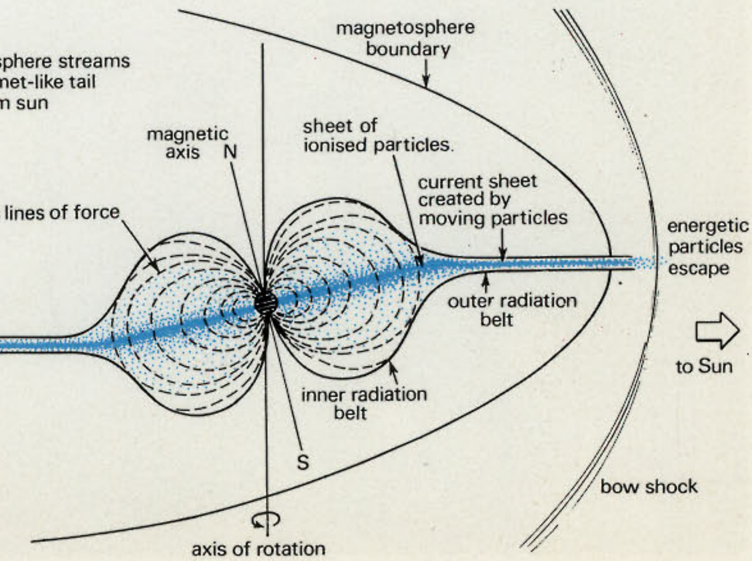

Plate 44

Plate 43 Jupiter's belts and zones

Plate 44 The Jovian magnetosphere

Plate 45 This image taken at a distance of 2 100 000 km from Jupiter shows the S-shaped flow patterns and intrusions in the North Tropical Zone

Plate 46 Jupiter from a distance of 1 840 000 km showing the plume in the equatorial zone. The white ovals, which have been observed by Earth-based telescopes, are seen in detail in the southern hemisphere

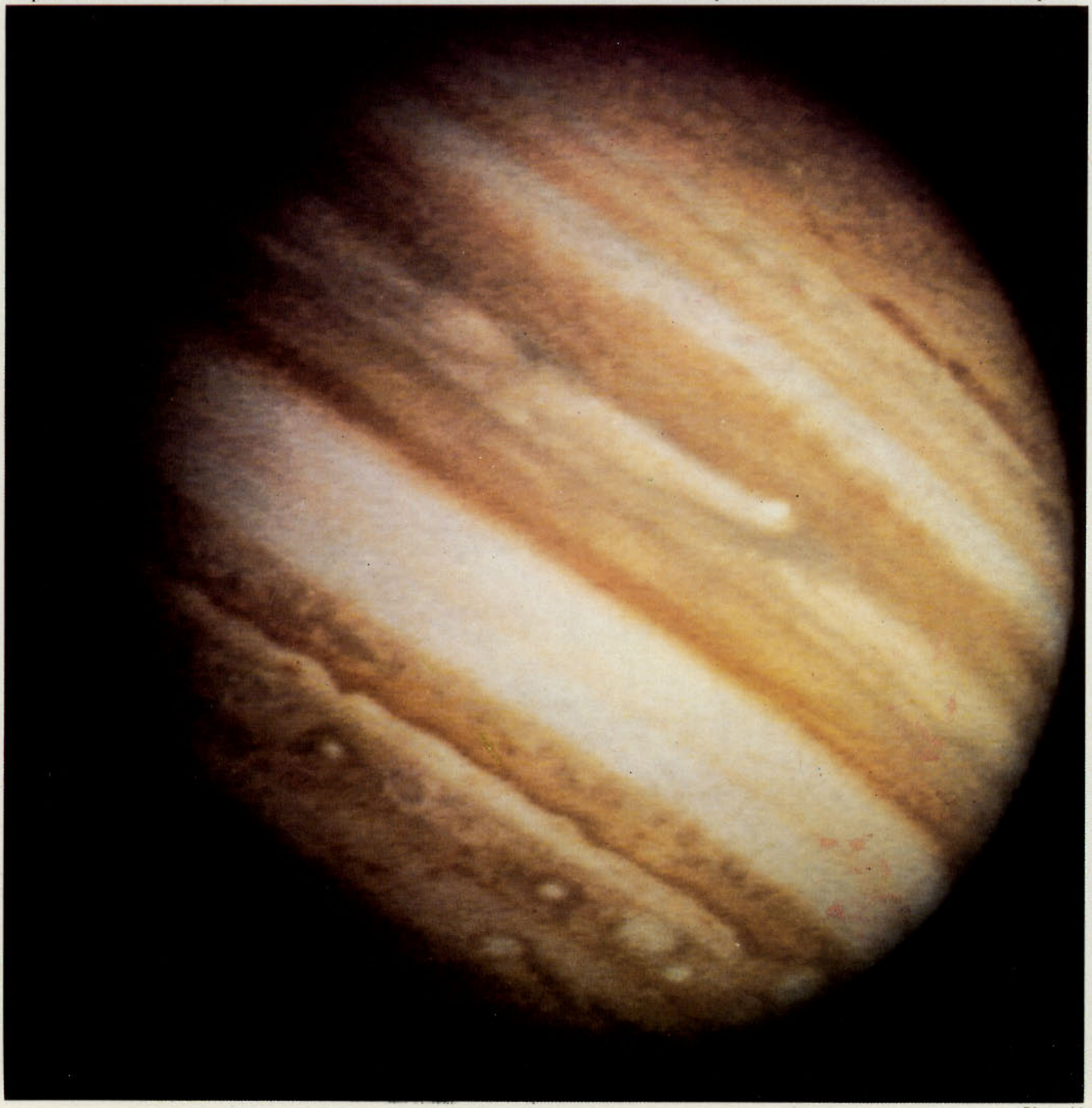

Plate 46

Plate 47

Plate 47 A close-up of Jupiter's North Temperate region taken from a distance of 1 300 000 km

Plate 48 An even closer view of the Jovian northern hemisphere taken from a distance of 992 000 km. This high-resolution picture clearly illustrates the complex motions on the belt/zone boundaries

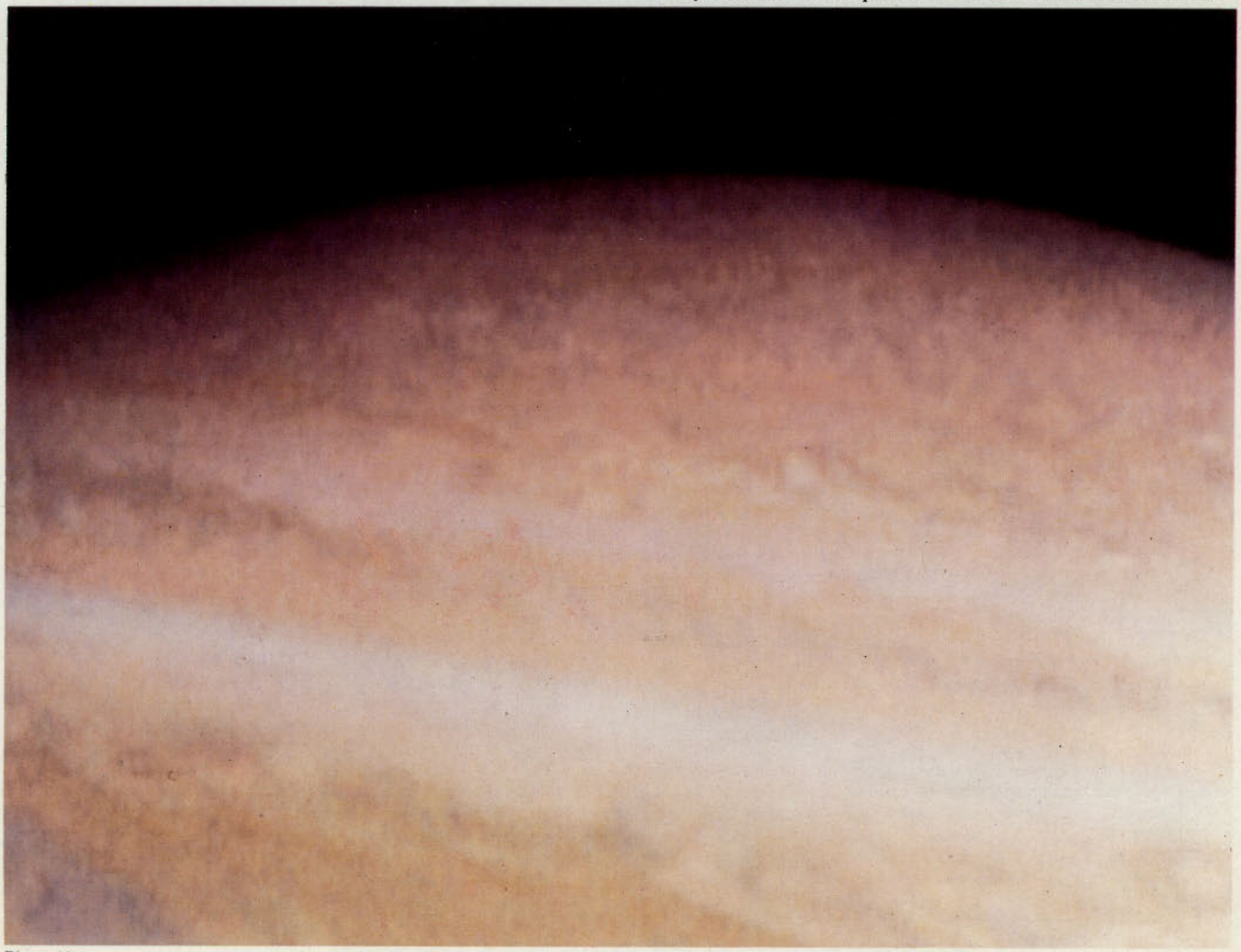

Plate 48

Plate 49

Plate 49 Saturn: a 60 inch photograph (Courtesy Hale Observatories)

TITAN: A SATELLITE WHICH RECYCLES ITS ATMOSPHERE

Saturn's largest satellite, Titan, some 5000 km in diameter and comparable in size to Mercury and Mars, is now emerging as one of the most intriguing objects in the solar system. For, despite its comparatively small size, Titan has an atmosphere dense enough to be examined spectroscopically from the Earth. The satellite is itself barely resolvable with a large telescope. Gerard Kuiper discovered methane in Titan's atmosphere 30 years ago; but what is currently exciting planetary scientists is that Titan is also surrounded by measurable amounts of hydrogen! How does this moon of Saturn come to have an atmosphere? and why does it not lose the lightest element of all very rapidly?

Titan is not merely small by planetary standards; it is also light (density about 2·0 g per cu. cm), thus further reducing its gravitational hold on fugitive gases. Inside, this body may consist, according to one model, mostly of ammonia dissolved in water, with a small amount of methane, and about one third composed of refractory oxides. The model implies an absence of water and ammonia from the atmosphere which may, nevertheless, contain nitrogen, and — like Jupiter's atmosphere — ethane and acetylene. The nitrogen could have evolved by photochemical breakdown of ammonia and methane (NH_3 and CH_4), releasing hydrogen, with photochemical formation of higher hydrocarbons. This orbiting chemical factory may, by the same token, have supplied Titan with a tarry surface.

Titan appears to have clouds around it which may or may not obscure the surface but probably give it its ruddy hue. The satellite may have a very high layer of haze formed of hydrocarbons which absorbs sunlight strongly. If so, it could provide an energy source to heat the upper atmosphere and, conceivably, cause temperature inversions.

Temperatures deduced from brightness measurements of Titan suggest that a "greenhouse effect" takes place, in which sunlight absorbed at one wavelength is re-emitted at longer wavelengths. In an atmosphere as cold as Titan's, however, the only known absorber of the appropriate infrared wavelengths is hydrogen under pressure. One analysis leads to the conclusion that a 50–50 mixture of hydrogen with methane could do the trick. The surface pressure would need to be at least 440 mb, and the temperature 155 K. A second model gives Titan a surface temperature of only 80 K and meets the brightness requirements by postulating a warm stratosphere. Whether or not Titan is, like Earth, a greenhouse depends on the atmosphere's thermal structure, which should prove amenable to further far-infrared observations.

Calculations show that if Titan had an atmosphere of pure hydrogen it would escape in only four hours! Admixture with heavier molecules would retard this rate somewhat, but the answer to how the satellite maintains hydrogen in its atmosphere at all, calls for a more radical solution. The answer very likely lies in the fact that, although the hydrogen would escape from Titan rapidly, it would be unable to leave the vicinity of the giant planet Saturn. Hence the escaped atoms should be found distributed in a hoop around Saturn through which Titan orbits, constantly exchanging hydrogen. An atom of hydrogen in such a torus would have a lifetime of six years equivalent to 140 orbits of Titan. The ring may be 20 Saturn radii wide and 10 Saturn radii thick, with 10 atoms per cu.cm.

Finally, if the surface pressure and temperature are high enough, Titan could well boast oceans of liquid methane.

Titan will form a major objective of the Mariner Jupiter-Saturn mission due to launch in 1977. Our first close-up views of this fascinating object may arrive in 1981.

in the Jovian stratosphere at about the 20-mb pressure level since the observed temperature profile is considerably warmer than that possible from the solar heating by the known atmospheric constituents.

This picture is, of course, greatly simplified since we have discussed only the large-scale features. Space missions such as Pioneers 10 and 11 now provide an opportunity to observe the breaks in the cloud tops, and study the local horizontal and vertical temperature gradients within the belts and zones which probably play an important role in the planetary energetics and in generating the rapidly changing colours we see. Certainly Pioneer 10's S-band experiment has presented atmospheric physicists with a puzzling and unexpected result. The temperatures they predicted in the upper Jovian troposphere are much higher than expected. At a pressure of 500 mb the occultation experiment gives a temperature of 400 K while the Pioneer 10 infrared radiometer measured the expected value of 130 K. The discrepancies are at present unclear. Clarification of the issue may provide important new insights into processes in Jupiter's lower stratosphere and upper troposphere.

JUPITER IN FOCUS

The images returned from Pioneer 10 have provided us with our first close-up look at the planet. At closest approach the resolution on the planet is reduced to approximately 200 km which is five times better than we can obtain from the Earth with perfect observing conditions. It has also provided our first opportunity to study the phases of Jupiter. From the Earth we see only one face of the planet since the phase angle (the angle between Sun, planet and observer) never exceeds 12°.

At a distance of $2\frac{1}{2}$ million km (about 35 R_J) from the centre of the planet, the image of Jupiter showed a face never seen before (Plate 42). The shadow of Io, and a wealth of cloud structure on a variety of scales, are clearly visible. The equatorial and polar regions seem much more uniform longitudinally than the midlatitude regions, which are very structured. The South Tropical Zone (Plate 43), which houses the Great Red Spot, and the South Equatorial Belt, are exceptionally bright and lacking in detail. These regions are apparently separated by a faint, thin, reddish belt. At a distance of about 26 R_J the spatial resolution improved to 800 km and the image showed a striking new feature in the equatorial zone (Plates 45, 46). A bright, well defined nucleus appeared with a plume, more than 80 000 km long, drawn out from the core. The core lies in the equatorial jet, and is the source of the plume, which it precedes in the flow. The plume is higher than the surrounding cloud tops and may have a polewards component of motion at higher levels in the atmosphere with a flow otherwise parallel to the equator.

Earth-based photographs have shown plumes at much lower resolution when festoon-like blue or purple structures have usually preceded the bright cores. These structures may be gaps in the upper clouds since they are regions of higher thermal emission from the planet. The plumes in the equatorial zone seem to have their origin near the northern edge of the equatorial belt, and both Pioneer and Earth-based radiometers confirm that we are observing the deeper levels of the atmosphere in these regions.

South of the South Temperate Zone, in the dark South Temperate Belt, the Pioneer images show elongated cloud forms about 1000 km wide in curving arcs about 5000 km in diameter (Figure 46). The boundary between the above belt and zone is extremely wavy with a wavelength of some 5000 km but does not show the arcing structures found in the South Temperate Belt near the South Tropical Zone. Further south, the South Temperate Zone is divided by dark, discontinuous filaments which have occasionally been observed from the Earth.

Jupiter's atmosphere is not symmetrical in its dynamical properties so that different features are evident in the northern hemisphere. North of the dark North Equatorial Belt, the light North Tropical Zone, which is a high cloud region, shows an extensive billowy wave structure and S-shaped swirls curving into the edge of the North Equatorial Belt. The swirls may be high clouds which veil part of this belt. Toward the poles, fewer features are evident, probably because the cloud layers are much lower there. These waves and eddies seen on the Pioneer pictures are examples of instabilities in the turbulent flow of Jupiter's atmosphere.

In the North Tropical Zone three "red" spots about a third of the size of the Great Red Spot have been seen by both Earth-based and Pioneer 10 observers. The lifetime of these spots is not yet known.

The most prominent feature in the Jovian atmosphere is the Great Red Spot which is situated at 22°S, is elliptical in shape, and occupies about 30° of longitude and 10° of latitude. Its dimensions are enormous and rather variable. First observed by Hooke in 1664, it has remained visible for more than 300 years. The Spot is the most permanent feature in the Jovian atmosphere. Throughout its life it has varied by only 1° in latitude, although it has shown considerable longitudinal variation. During the last 100 years it has wandered through about 1200° of longitude. In the Pioneer images the Spot shows a darkish border with points at its east and west extremities. Indeed, its shape is rather variable. There is also the suggestion of a ring of darker material within the GRS suggesting that the overall cross section may be greater than the active region. Some of the high-resolution pictures show cellular structure and also suggest that there may be convective activity within the Great Red Spot. We have known from Earth-based studies that the circulation is anticyclonic in the neighbourhood of this infamous feature which, since it lies in the southern hemisphere, means a rising motion

To explain any features observed in planetary atmospheres we must, at first, use our knowledge of terrestrial weather systems. Since the Jovian atmospheric motions are internally driven, so that heat is fed in from the bottom of the atmosphere, the convective systems may resemble those we observe in the terrestrial tropics. In the Earth's tropical atmosphere the amount of organised convective activity along the so-called intertropical convergence zone is dependent on the depth of penetration of the associated high-level vortices and the low-level factors which affect convection, e.g. the sea surface temperature, and moisture content.

On Jupiter, a steady-state storm is possible. There is no daily temperature variation in the Jovian atmosphere to limit the lifetime of a convective disturbance as on the Earth. Certainly the ubiquitous light and dark spots we observe on Jupiter are probably regions of local storms. Their colours are probably associated with their composition, and therefore with the altitude of the cloud tops.

The Great Red Spot may also fit into this picture. It is difficult at this stage to account for its uniqueness, which may be associated with some unseen surface irregularity or the result of a chance capture of a planetary body. The high-resolution pictures to be

taken during the Mariner-Jupiter-Saturn fly-by in 1979 may help to resolve the origin of this feature. Until then it will remain a "whirlpool of emotion" although there is increasing evidence to suggest that it is a meteorological phenomenon, and a manifestation of Jupiter's atmospheric motions.

A second spacecraft, Pioneer 11, with identical scientific instruments to those carried on the sister craft, has now flown past Jupiter. It reached the planet on 3 December 1974. The spacecraft had been retargeted to fly by Jupiter on a south-north trajectory inclined at 55° to the equator with a closest approach of 1·6 R_J. This flight path minimised the time the spacecraft spent in the hazardous radiation belts, while scientifically it provided an opportunity to observe the higher latitudes of both hemispheres and the Jovian environment out of the equatorial plane. Pioneer 11 will travel across the solar system once more to encounter Saturn in late 1979, 1740 days after the Jovian encounter.

SATURN AND BEYOND

SIMON MITTON

By comparison with the inner regions of the solar system, our knowledge of the outliers beyond Jupiter is rather scanty. The reasons for this are not hard to discover: Saturn is never nearer to Earth than about 1·3 billion kilometres, and Uranus, Neptune and Pluto are so much farther away that they can only be investigated satisfactorily with large telescopes. Furthermore, spectacularly successful space probes have scrutinised and photographed the planets from Mercury to Jupiter in considerable detail, but no hardware has yet reached the outer planets and it seems unlikely that any will do so in the foreseeable future. The favourable juxtaposition for a planetary "Grand Tour", taking in some of the more distant planets and employing the gravitational fields of successive planets to modify the spacecraft's trajectory, is past.

Despite this somewhat depressing scenario, the outer solar system has attractions for casual celestial sightseers, planetary scientists, and historians of science. For example, few wonders of the sky rival the beauty of Saturn's rings, which are currently clearly visible through even a small telescope. Moving out farther we encounter Uranus, which was unknown to the ancient astronomers, although it is occasionally visible to the naked eye. Studies of Uranus played a critical part in unravelling one of the great astrophysical mysteries of the early twentieth century: the chemical constitution of the atmospheres of the giant planets. In the previous century a careful analysis of the motion of Uranus had resulted in a brilliant triumph for dynamical astronomy when J. G. Galle, of the Berlin Observatory, detected a new planet, Neptune, close to its predicted position in 1846. Analysis of the perturbations in the orbits of Uranus and Neptune eventually led to the detection of Pluto in 1930. Little is known about this remote and cold world some 6 billion kilometres from the Sun. Is it the last major outpost of the solar system? There have been many false alarms in the fascinating search for a transplutonian planet but it now seems unlikely that any significant planets reside beyond Pluto.

ATMOSPHERES OF THE GIANT PLANETS

Dense cloud layers shroud the outer giants, and give them considerably higher reflectivities than those of the terrestrial planets. The general aspect of Saturn is similar to Jupiter, although the belts are not so clearly defined, and they do not appear to undergo the rapid changes associated with Jupiter. Uranus too shows a faint structure of belts under excellent observing conditions. In each case the coloured bands are due to the global circulation patterns of cloud structures in the upper atmospheres, the rotation speeds of which increase by several minutes as one moves from the equator to the poles. Jupiter, Neptune, Uranus and Saturn have rotation speeds of 10 to 15 hours, and these high values cause considerable distortion to the shape of the planet. Saturn, for example, is bloated by around 10 per cent at its equator.

The constitution of the great cloud decks was a mystery to astronomers for over 60 years. A distinguished Italian astronomer, Angelo Secchi, and the English amateur William Huggins were the first to use the spectroscope to reveal the curiosities of various celestial bodies. Turning the spectroscope onto the major planets they discovered wide and dark absorption bands, particularly at the red end of the spectrum. Secchi noted this for Saturn in 1863, and found even wider bands for Uranus and Neptune in 1869, remarking that the atmospheres of these planets were "not yet cleansed". Many ideas to explain the pollutants were put forward, but none succeeded until 1932.

In the end Jupiter supplied the vital hint. Rupert Wildt eventually extended the observable spectral range out to the near infrared and there discovered three new sets of absorption bands whose intensity surpassed those in the visual region. Because the bands accumulated towards the red end of the spectrum he correctly surmised that vibration-rotation transitions in molecules were implicated. By reference to contemporary research then being carried out by physical chemists, Wildt matched one Jupiter band, at 8860 angstroms with a band in the spectrum of methane. Inspired by this success he then calculated three further probable frequencies for methane transitions, and was able to match each one with bands in the planetary spectra. He concluded his paper on these results with a plea for more laboratory data on the methane spectrum and urged observers to seek the 8860-angstrom band in the spectra of Saturn, Uranus and Neptune. Physicists rapidly confirmed Wildt's predictions, and they also obtained the spectrum of ammonium, which matched many of Jupiter's remaining absorption lines.

Complete proof that the absorption bands are caused by methane came in 1934. V. M. Slipher of Lowell Observatory toiled ceaselessly to improve planetary spectroscopy. Uranus rewarded him richly, when he finally pushed photographic spectroscopy of it out to 8500 angstroms revealing many deep and intense bands. In collaboration with A. Adel he next calculated all possible vibration-rotation transitions of methane, and obtained the laboratory spectrum at a pressure of

40 atmospheres. They found that nearly all intense lines in the spectrum of Uranus matched precisely their spectrum of methane. Altogether 36 bands in Uranus and Neptune came from methane; in fact, this gas is the major observable constituent of the atmospheres of Uranus and Neptune. Jupiter and Saturn also possess substantial amounts of gaseous ammonia. In the darker belts across the planets, marking the global wind patterns, traces of solid crystals, dust and complex organic molecules may be responsible for the dark colouring.

INSIDE THE GIANT PLANETS

Although we can observe the atmospheres of the giant planets, the mysteries of their internal structures will yield only to theory and model-making. Many theorists have tried to make models which concur with the major physical properties. Among these the most striking are the low densities, only 0·7 that of water in the case of Saturn. This has led to the basic assumption that the bulk of the mass must reside in hydrogen and helium; these are not only the lightest elements but they also have the highest cosmic abundances. A second ingredient of the models is an assumed picture of how planets must have formed in the primaeval solar nebula. Recently M. Podolak and A. G. W. Cameron, two planetary scientists working in New York, have assembled a new range of models to describe the structures of the outer planets.

One common feature is that each planet is thought to contain a rocky central core. This has formed from metallic and silicate crystals that condensed in the interstellar cloud from which our solar system originally arose. In the case of the terrestrial planets this rocky body is virtually all that now remains, solar heating having driven away the lighter gases. Jupiter may have a solid core 40 times as massive as Earth. For Saturn, Uranus, and Neptune the cores are about 20, 4 and 3·7 times the Earth's mass. Surrounding these cores there are probably layers of frozen water and ammonia. For Uranus and Neptune the ice may have twice the mass of the rocky core, and form a layer about 15 000 km deep. Jupiter and Saturn probably have much smaller icy envelopes imprisoning their rocky interiors.

Above the frozen wastes we encounter the thick cloudy atmosphere of hydrogen, helium, water, ammonia and methane, the latter being the principal contributor to the features in the spectrum. In the case of Jupiter the atmospheric pressure at great depths exceeds 3 million atmospheres before the ice layer is reached. This great pressure crushes the normal atomic structure of hydrogen, so that the resulting dense gas has free electrons and its electrical properties are similar to a metal. Only Jupiter is sufficiently massive to have this metallic hydrogen zone, which probably helps to sustain that planet's extensive magnetic field.

Rock and ice together make up 75 to 85 per cent of the mass of Uranus and Neptune. The reason why the outer planets have low overall densities is that the gaseous atmospheres are much more extensive than the dense cores

SATURN'S RINGS

In the case of Saturn, the structure of the diaphanous rings has attracted at least as much attention as the physics of the interior. Altogether there are four rings; the innermost one is very inconspicuous and so it was not discovered until 1970. The radius of the entire system is 140 000 km, and the width of the broadest ring is 26 000 km. About every 15 years the rings are presented to the Earth edgewise, and they are then practically invisible. It is therefore unlikely that the system is more than 10 km thick. Distant stars and the surface of Saturn can be seen shining right through the rings, so that it cannot be a solid structure. Rather the heavenly haloes are composed of a myriad of particles, each one behaving like a miniature satellite revolving round Saturn. Gaps between the rings are caused by resonant perturbations of Saturn's major satellites.

Surprising results were obtained in 1973 when a radar beam was aimed at the rings of Saturn by a 400-kW transmitter. According to two scientists at Pasadena's Jet Propulsion Laboratory, R. M. Goldstein and G. A. Morris, unexpectedly strong echoes came bouncing right back, after a round trip lasting more than two hours. Only chunks of rock and metal could account for the high reflectivity. It now seems likely that included in the delicate ring system are substantial rough and irregular stones up to one metre or possibly even larger, in size. Some metallic particles may be swimming around as well. Furthermore, faint radar echoes are returned from regions beyond the visible rings, and so a sprinkling of boulders exists outside them.

Radio and infrared measurements indicate that the rings also contain ice and silicate particles with a mean radius of about one cm. These particles have rough surfaces and possibly an icy surface layer. They are cigar shaped, and orbit with their long axes directed at the planet. It is probable that the mean particle size is being continuously degraded by collisions within the ring system and meteoroid impacts from outside.

PLUTO AND BEYOND

Pluto has an eccentric orbit that cuts across the orbit of Neptune, so that it is not always the last outpost, although it does have the largest mean distance from the Sun. Several facts suggest that Pluto is actually an escaped satellite of Neptune. It has a much smaller mass and size than the Jovian planets, but it is quite similar to their satellites. The crossing of the orbits also shows that the two objects could once have been dynamically linked. Pluto has an orbital plane inclined at 17° to the rest of the solar system, and this suggests that it has had a different history to the other planets. In 1973 it was found that its rotation axis is tilted at 50° to the orbit; only Uranus has a larger inclination. If it is an escaped satellite there are dynamical problems to be solved because any interaction of this type has to involve at least three bodies, and there is no telling which object was the third party in the ejection of Pluto.

According to some authorities even the discovery of Pluto has not ensured complete harmony in the heavens, and many have thus attempted to predict the position of an alleged transplutonian object. Every few years someone claims to have narrowed down the search to a small area of sky, but transpluto has never been found. The present situation is that the residuals in the planetary orbits are now so small that any further planets must be insignificant. Certainly they will be fainter than 16th magnitude, and therefore hard to detect as their motion will be slow; it is unlikely that anything as large as the Earth is lurking beyond the present boundaries of the solar system. As estimates of the masses of the known planets improve it is possible that the residuals will disappear entirely. Gravitational theory looks unlikely to complete a hat-trick of planetary discoveries.

THE DEBRIS

KEITH HINDLEY

Up to 30 years ago, serious professional research on interplanetary material had been on a very modest scale—investigations up to that date had been made largely by amateur astronomers. After World War II there was some improvement, but it was the impetus provided by the start of the space-age 15 years ago that led to sophisticated modern observing techniques being applied to the small bodies of the solar system. Fast electronic computers, radar methods applied to meteor astronomy, the use of large modern telescopes for comet work, and the recent sophistication of observations from satellites above the Earth's atmosphere have all helped to revolutionise work in this field. The increased use over the last few years of observations in wavelengths away from the visible part of the spectrum promises to provide a new, and perhaps even more important, advance in observational methods.

Fifteen years ago the contemporary picture of the interrelations of comets, meteors and asteroids gave a deceptively simple system. The meteors were fragile dust-balls dispersed by comets into meteor streams, sporadic meteors being scattered ancient streams. The larger, more solid bodies which produced fireballs and meteorite falls were fragments from asteroid collisions. This attractive model was to undergo severe modifications.

THE MODERN PICTURE OF COMETS

The first applications of modern observing techniques to comet research began in the late 1950's, at the start of the space age. Advances came with the appearances of particularly prominent or bright comets — such as Arend-Roland and Mrkos in 1957, Seki-Lines in 1962, Ikeya-Seki in 1965, Bennett (Figure 1) in 1970, and Kohoutek in 1974. The first high-resolution spectra of a cometary head and tail were taken of Mrkos in 1957, and showed great detail in the molecular bands of such systems as CN, NH_2, C_2, C_3, etc, superimposed on the continuous spectrum reflected by dust-particles. Well defined Doppler shifts in the positions of some lines gave the first detailed information on the movement of material near a comet nucleus. Comet Ikeya-Seki of 1965 was a member of the Sun-grazing family of new comets, and passed within 290 000 miles of the solar surface in October 1965. At such small solar distances the heating was intense, and high-dispersion spectra clearly showed strong emission lines due to sodium, calcium, iron, nickel, chromium and other metals, presumably from vaporisation of stony and metallic dust-particles. The motions of gas and dust in comet tails have been the subject of much research, and have greatly improved our understanding of the solar wind. Observations of comets during the period when the Earth passed through their orbital planes has abundantly confirmed just how widespread is dust emission from bright comet heads. Arend-Roland, Seki-Lines and Kohoutek all exhibited sheets of such dust as well-defined sunward anti-tails. Infrared examination of Bennett clearly showed a spectral peak at 10 micrometres, identified as being caused by silicate dust and confirming the high dust density in cometary heads. Ultraviolet observations by orbital satellites discovered a huge halo of hydrogen gas surrounding the head of comet Bennett, and a similar one was found accompanying Kohoutek.

Observations of this latest bright comet have been made in a vast number of wavelengths, and it will take a year or more to digest the data which has been collected. Observations recorded during the Skylab programme will be particularly valuable; and Mariner 10, en route to Mercury and Venus, recorded very useful observations in the ultraviolet. The detection of water vapour as H_2O^+ in the tail, and an ice-grain halo around the nucleus of Kohoutek lends gratifying support for the icy-conglomerate model for comet nuclei. But perhaps the most interesting discovery is the detection of CH CN and HCN in Kohoutek by radio astronomers. These are pretty complex molecules never before seen in comets, but found in considerable concentrations in deep interstellar space.

It has become increasingly clear that unusual events such as comet outbursts and breakups are much more frequent than had been imagined. Many comets in recent years have shown sudden increases in brightness, possibly due to the sudden release of surface material from a hard-baked and overheated region of the nucleus. Many recent comets have also shown nuclear breakup on photographs taken with long-focus cameras. The Sun-grazing comet Ikeya-Seki in 1965 showed a whole series of small secondary nuclei after its close approach to the Sun, but even relatively inactive comets at large solar distances have shown multiple nuclei.

Figure 1 Comet Bennett photographed 4 April, 1970 by Dr H. R. Soper from the Isle of Man. Note the thin gas tail curving to the left and the main dust tail curving right. Bennett reached magnitude −1 and was very well placed for lengthy observations against a dark sky (unlike Kohoutek in 1974)

These observations are difficult to reconcile with a sand-bank model for the cometary nucleus, and the majority of comet workers now favour the solid icy-conglomerate model of Professor Fred Whipple.

The family of periodic comets has furnished astronomers with a steady stream of objects for physical and orbital studies. Periodic comets clearly fade rapidly, becoming steadily fainter at each return to the vicinity of the Sun. They lose from 0·1 to 1 per cent of their mass at each revolution of their orbit and, with the orbital period of many comets being below 10 years, their lifetimes must be reckoned as just a few thousand years at most. The application of modern computer techniques, and improved masses for the planets, has enabled detailed orbital studies of periodic comets to be made. In nearly every case, however, it has been found impossible to fit the observations with gravitational theory. Non-gravitational forces seem to be acting on the comets. These are generally radially outwards from the Sun—probably caused by the reaction from the emission of gases and dust from the heated sunward side of nuclei. Periodic comets with steadily increasing non-gravitational effects may be heading for complete vaporisation, while those with steadily decreasing effects may contain a hard compact stony core in the nucleus, and will probably ultimately evolve into asteroid-like bodies which cross the orbits of Mars and the Earth in the manner of Apollo asteroids.

COMETS LINKED WITH METEORS

The last 15 years has seen the association between comets and meteor streams strengthened. As well as the half dozen or so cases where there is little difference between comet and meteor stream orbits, detailed investigations have suggested associations between scattered meteor streams and some comets whose orbits do not make particularly close approaches to the Earth's orbit. Thus the Taurid meteors have been convincingly linked with comet Encke, whilst the η-Aquarid and Orionid meteors seem to be linked with comet Halley. Computers have been used to investigate the evolution of meteor stream orbits over considerable periods, and from this work it has become clear that stream orbits can evolve very rapidly indeed. Thus the Quadrantid meteor stream orbit has evolved from one of 15° inclination to one of 70°, one of perihelion distance 0·09 astronomical units to one of 0·95 AU in only 1800 years.

The meteor shower event of the period was undoubtedly the very extensive Leonid meteor storm of 17 November, 1966. The Leonid meteor stream had given spectacular displays of meteors in 1799, 1833 and 1866. However, few meteors were seen in 1899 and 1933, and many scientists were sceptical about a good display in 1966. In fact, it turned out to be the most intense display in meteor history — after a steady climb in activity over several hours, Leonid meteor rates suddenly peaked sharply over a few minutes at 150 000 meteors an hour, and awed observers in the western United States witnessed 40 meteors per second raining down in the pre-dawn sky. The storm aroused considerable interest in the Leonid stream and its associated comet — Temple. It seems that the 1966 display was caused by a thin compact new filament of particles which left the parent comet as recently as 100 years ago.

The embarrassingly prodigious output of the super-Schmidt meteor cameras in the 1950's, led to a large amount of detailed and accurate orbital data for naked-eye range meteors, and much investigation of individual streams and the sporadic meteor complex has been carried out. The decelerations of these meteors suggested that most meteoroids were composed of very fragile dust-ball structures of low strength, although there were considerable variations in individual meteors within this model. Recently there has been a change of view here. Many workers now believe that meteors are composed of a gas-rich primitive form of carbonaceous chondrite material rather than dust-balls. Sophisticated radar equipment now enables observations to be extended to meteors very much fainter than can be seen with the naked eye or meteor cameras. It was found that the meteor streams become less important at faint magnitudes — the background sporadic meteors dominating the meteor activity among faint meteors. In the last few years, the application of modern image-orthicon techniques has enabled meteors as faint as magnitude +12 to be observed using photographic techniques — thereby covering much the same region as the radar work.

As well as interest spreading to fainter meteors, it also spread to brighter ones. The successful accidental photography of the Czech magnitude −19 fireball of 7 April, 1959 which led to the Pribram meteorite fall, demonstrated that bright meteorite-dropping fireballs could, in principle, be photographed. As a result, three networks of automatic cameras were set up covering large areas of the American and Canadian Prairies, and most of Czechoslovakia and West Germany. These networks cover some 3 million sq. km of the Earth's surface and are intended to photograph rare bright fireballs to predict the impact points of meteorites falling from them. The networks were highly successful, but yielded quite unexpected results — it seems that fireballs are about 10 times more frequent than expected, but paradoxically, less than 1 per cent of these bright meteors actually leads to a meteorite fall. Most fireball-producing bodies seem to be composed of fragile material, possibly of cometary origin, which is destroyed in the Earth's atmosphere before it can decelerate to free-fall velocity and drop meteorites. To date, only one meteorite fall — that of Lost City, Oklahoma in 1970 — has been recorded although the two original networks have now been operating for over 10 years. The solid meteorites with which we are now familiar in museum collections clearly make up only a small fraction of fireball parent bodies, but these few may come from the asteroid belt rather than from comets. The old idea of all bright meteors having this origin had to be abandoned when detailed computations indicated that the supply of such bodies being perturbed or ejected from the asteroid regions by collisions, was wholly inadequate to explain the total observed flux of meteoritic material in the vicinity of the Earth.

SAMPLES FROM SPACE — GRATIS

Meteorites present the scientist with free (or at least very inexpensive) samples of interplanetary material, and research on them has blossomed in the last 15 years. The recovery of fresh meteorite falls has been pursued with great alacrity, and as a result, many falls have been recovered from developing countries where falls went unreported previously (Figures 2 and 3). The last decade has therefore seen a steady increase in the number of fresh falls recovered, and this has stimulated interest in the analysis and study of meteorites. Improved analytical and petrological techniques have enabled the 2000 or so known

meteorites to be classified into types and sub-types with great precision. Studies have shown that certain meteorites seem to have been little affected by heat or pressure (the carbonaceous chondrites for instance) while other types clearly show indications of heat or pressure modification. The study of the internal make-up of iron meteorites has led to figures for the cooling rates which various irons experienced after being in a molten state. The variation in chemical composition coupled with the various cooling rates indicates that 90 per cent of iron meteorites came from at least 6 and possibly 11 parent bodies, all but one of which was larger than 200 km diameter. Cooling rates for chondrite stony meteorites, the commonest meteorite type, indicate at least 5 but possibly as many as 10 parent bodies, with diameters in the range 180 to 300 km. Potassium/argon and uranium/helium dating of stony meteorites indicates that perhaps as much as 60 per cent of these bodies was released in a single catastrophic collision event some 520 million years ago.

The use of radioactive measurements of meteorites, cosmic-ray exposure dating, and the study of various isotopic abundances are all techniques which have been extensively developed over the last 10 years. These have indicated that practically all meteorites, the Earth, and the Moon were all formed some $4{\cdot}6 \times 10$ years ago, within a relatively short 100-million-year period. Other studies indicate when individual meteorites have suffered major shock events, when they were released from larger bodies by collisions, and even reveal the pre-atmospheric size and shape of a fragmented meteorite found on the Earth's surface. At the moment, the study of new dating methods using novel interpretations of known abundances is adding confirmatory data on meteorite ages to results deduced by more classical methods. As techniques improve, and the processes affecting isotopic abundances are better understood, we can expect the accuracy of dating information to improve and give a much clearer picture of the early history of meteorite parent bodies.

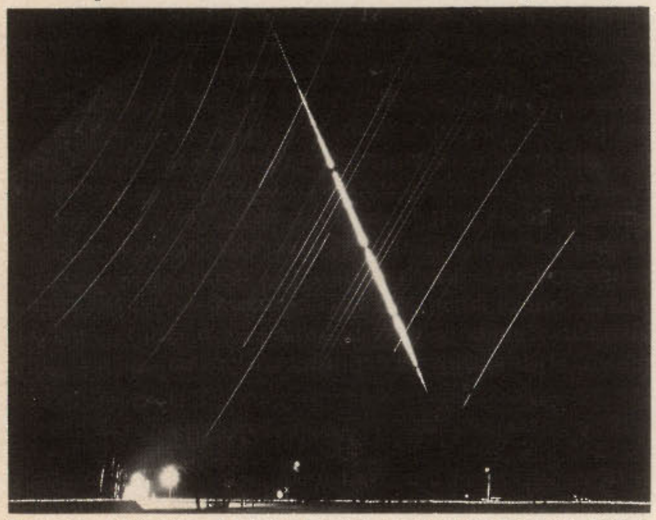

Figure 2 At 8.14 pm local time on the evening of 3 January, 1970, a brilliant magnitude −12 fireball descends into the Earth's atmosphere over Oklahoma. The fireball lasted 9 seconds, and decelerated to free fall velocity at a height of 19 km. Meteorites were predicted to have fallen near Lost City, Oklahoma

Figure 3 Intensive field searches near Lost City, Oklahoma during January 1970, yielded four meteorite specimens, which fitted together as shown above. This meteorite followed an oriented flight before fragmenting, the heavily ablated curved face facing the direction of motion.

TEKTITES

Tektites are small glassy objects found in considerable quantities in several localities in the world. Their properties set them aside from almost all other terrestrial objects and, until quite recently, scientists were not quite sure precisely what they had to deal with.

Tektites are composed of a completely amorphous glass, which shows glass inclusions and exhibits beautiful external and internal flow structures. These suggest that the glass was at some time extremely fluid — perhaps at a temperature of more than 2000°C, and this is confirmed by their extraordinarily low water content. They seem to have suffered rapid fusing followed by fairly rapid quenching. These features distinguish these objects from all other terrestrial glasses, and seem to rule out a terrestrial volcanic origin for tektites. Metallic spherules with a composition not inconsistent with meteoritic iron have been found in some types of tektite and, in addition, tektites do share many features of impact glass found at authenticated meteorite impact sites. This does perhaps imply that tektites were produced in an impact event. The history of tektites is now pretty well mapped — at some time in the past surface rocks on an unknown planet were shock melted by meteorite impact and then rapidly quenched. The solidified glassy objects were then further heated at re-entry into the Earth's atmosphere after an undetermined time. This period cannot have been lengthy, as tektites show no evidence of cosmic-ray exposure — aluminium−26, cosmogenic neon or cosmic-ray tracks — and so have travelled neither far nor long in space. This evidence immediately limits the site of origin to the Earth and Moon.

Recent work has furnished accurate dating information suggesting close links between two tektite fields and known meteorite impact craters. The dating of impactites at the Ries crater in Germany is 14·8 million years, exactly the age of the Czechoslovakian tektites, and both were melted from rocks about 300 million years old. Impactites from the Lake Bosumtwi crater in Ghana have been dated at 1·3 million years, the same age as the Ivory Coast tektites, and again, both these were formed from rocks of about the same age — 2000 million years. The North American and far eastern tektite fields do not seem to have a recent terrestrial impact crater with which they can be associated, but a recent detailed study has suggested that the very extensive far eastern field can be linked with debris ejected by the impact which produced the crater Tycho on the Moon.

Much work still needs to be done, the current situation being that there is still no completely satisfactory explanation for any of the four tektite fields. Although meteorite impact now seems to be established as the basic mode of formation, the site of that impact, and the detailed processes involved, are still a matter for debate and intensive research.

At the start of the space age, the nature of the asteroids was largely unknown. Asteroid studies were not then fashionable, and work in the previous century had been concentrated on finding new asteroids and making positional measurements of them to determine their orbits and ensure that they could be identified in future. By the late 1950's, over 1700 bodies had well determined orbits.

Early measurements of the colour indices of asteroids provided little useful information about theii composition. However, it was soon realised that the light reflected by most asteroids varies in a periodic fashion, suggesting an irregular rotating body presenting a varying frontal area to the Sun. These asteroidal rotation periods vary considerably, but generally fall in the range 4 to 14 hours.

Only in the case of the first four asteroids, 1 Ceres, 2 Pallas, 3 Juno and 4 Vesta, is it possible to measure diameters directly at the telescope. But even with the additional sophistication of double-image micrometers, interferometers and diskmeters, and the additional measurements from occultations of asteroids by the Moon, the results are of poor accuracy. However, using these figures with the known absolute brightnesses, the albedo, or reflectivity, of the major asteroids was deduced. This mean albedo was then used with the brightnesses of other asteroids to deduce approximate diameters for them. the first column of figures in the table below shows some of the definitive results using this method. It was published in 1971.

At about the same time, the first reasonably sound estimates of the masses of 1 Ceres and 4 Vesta were published. The mutual perturbations of pairs of large asteroids during close encounters were used to determine these masses. When used with the diameters deduced above, they gave mean bulk densities of more than 5 g/cu. cm — uncomfortably high values.

During the 1950's and 1960's modern fast computer techniques eased the mammoth task of keeping track of the increasing number of asteroids and their orbits. In the direct observation field, photoelectric photometry enabled better rotation periods, and shape and rotational axis data, to be deduced, but spectrophotometric measurements could do little but give rough indications of surface compositions. In general, practically every physical factor of asteroids being investigated was still giving order-of-magnitude results; our knowledge was still very sketchy.

RECENT ASTEROID STUDIES

Then, in 1970, the rapid development of entirely new observational techniques revolutionised asteroid studies. Two completely new methods for determining asteroid albedos and diameters were introduced. The first utilises recent advances in infrared astronomy. If the absolute visible wavelength magnitude of an asteroid (a surface parameter) is known, measurement of the thermal infrared magnitude between 10 and 20 micrometres (a bulk parameter) allows the albedo of the body to be determined from the ratio of visible to infrared brightness. The diameter follows from the known visible brightness. The second method involves a relationship recognised some time ago between the albedos of materials and the polarisation of sunlight which they reflect. The degree of polarisation varies with phase angle. At small angles it becomes negative, but then it rises again to more positive values in a straight-line relationship. The slope of this rising branch is closely correlated with albedo, and is quite independant of such physical parameters as particle size and other surface conditions. Again, the asteroid albedo leads directly to the diameter. Results from both these new methods are shown in the table below, and are compared with results from classical procedures.

Asteroid	Diameter (km)		
	Classical	Polarimetric	Radiometric
1 Ceres	767	1050	1000
2 Pallas	489	560	530
3 Juno	193	225	240
4 Vesta	386	515	530
8 Flora	129	155	170
15 Eunomia	225	225	240
532 Herculina	103	120	170

It is clear that these bodies are much larger than suggested by classical measurements, mainly due to the low albedos — typical values are from 10 to 20 per cent. A few of the asteroids are extremely dark, 324 Bamberga for instance, reflects only 2½ per cent of the sunlight it receives, and so is actually darker than carbon black. These new diameters enable new densities to be computed for those asteroids whose mass is known. The new figures of 2 to 2½ g/cu. cm are much more reasonable, being similar to the densities of the carbonaceous meteorites.

A breakthrough in asteroid spectrophotometry also occurred in 1970, when workers at Massachusetts Institute of Technology began making measurements of asteroids through 24 narrow-band filters extending from 0·3 micrometres in the near ultraviolet to 1·1 micrometres in the infrared. These spectra have been compared with laboratory measurements of over 100 powdered minerals in various physical states. The commonest asteroid surface material is found to be that of carbonaceous chondrites, thereby explaining the dark reflectivity of asteroids in general, while surfaces similar to basaltic achondrite, mesosiderite, nickel-iron, enstatite and anorthosite meteorites have also been

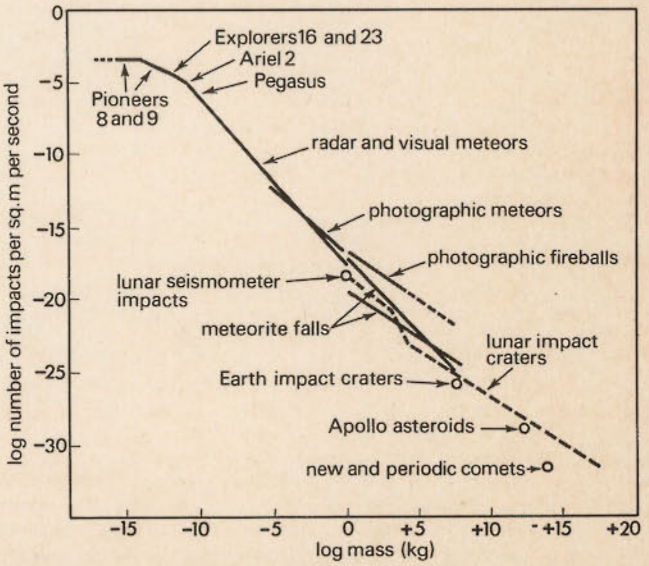

Figure 4 An up-to-date plot of the space density of particles of all sizes at present in the vicinity of the Earth. The cumulative impact rate per sq. m is plotted against the mass of individual particles. The plot is derived from all the latest information for particles from cosmic dust size through meteor particles to asteroids and comets. Satellite measurements suggest that there are few dust particles with masses below 10^{-16} kg

found. Ordinary common chrondrite asteroid surfaces are rare in the sample studied so far.

New data on the present distribution of asteroid brightnesses (and therefore masses) as faint as magnitude +20, also published in 1970, have now been used to investigate how the asteroid belt has evolved. Most scientists now agree that the system began with a distribution of bodies up to 1000 km diameter which formed early in the life of the solar system. Lengthy calculations with modern computer techniques suggest that the asteroids as we now see them are in a highly fragmented state, having suffered many mutual collisions (Figure 6). It seems that 1 Ceres, 2 Pallas and 4 Vesta may be the only three large bodies from the original distribution which have survived unshattered to modern times.

RELATING THE SPACE FRAGMENTS

It is clear that the deceptively simple picture of the interplanetary debris system held 15 years ago has been almost completely redrawn. Now that the distribution of the various types of interplanetary material is known in detail (Figure 4), it has been possible to examine various models of the whole interacting system, and to draw conclusions about the system's stability and make-up. Most micrometeoroids are expelled from the solar system by radiation pressure shortly after their release, while drag forces acting on particles just large enough to survive expulsion will cause them to spiral into the Sun fairly quickly. Meteoroids in the radio, visual and photographic ranges are now being destroyed predominantly by catastrophic collisions with other particles of similar mass. This loss is not being replaced by secondary fragments released from collisions between larger bodies, but it seems that the comets supply sufficient fresh meteoroids to make up the collision loss. The survival of large objects is currently being limited by planetary perturbations moving them away from the region of the Earth, and by catastrophic collisions with other large bodies. The observed distribution of stony meteorite exposure ages is consistent with this model.

It is now felt that while ordinary meteors are certainly the products of comet release, the asteroids cannot supply enough debris in Earth-crossing orbits to explain the flux of large meteoroids near the Earth. The majority of large bodies may be composed of friable carbonaceous chondrite material of a primitive type, originating in some asteroids of the Apollo type, which may themselves be the extinct nuclei of old periodic comets rather than true asteroids. The small numbers of large bodies which lead to solid meteorite falls are most likely true asteroid debris deflected into Earth-crossing orbits from the asteroid belt by favourable repeating perturbations by Jupiter or perhaps Mars.

The recent rapid diversification of observing techniques used on interplanetary material will mean that a vast amount of information will be forthcoming in the next few years. But perhaps the most exciting prospect at present is satellite rendezvous with asteroids or comets. Detailed planning for both types of mission has been going on for some time, and it should now be a few years only before scientists will be able to receive data from satellites in close proximity to both asteroids and comets. Plans are also being made for a soft-landing mission to one of the Apollo asteroids, with surface samples being collected and returned to Earth. Laboratory study of primitive asteroid materials will add greatly to our knowledge of the conditions prevalent in the earliest period of solar system history and improve our understanding of how the whole planetary system has evolved in the last 4 to 5 thousand million years.

FUTURE MISSIONS ♅ ♆ ♇

GARRY HUNT

1974 has been the "Year of the Planets". In this twelve-month period spacecraft from the Earth have journeyed to Mercury and Venus, landed on Mars, passed through the asteroid belt, explored the Jovian environment and the interplanetary medium beyond this major planet toward the orbit of Saturn.

But from the exploration of Mercury, Venus and Mars we learn only a small amount about the solar system as a whole. Indeed it is the outer solar system we need to explore. The region of the huge rapidly rotating, low-density planets, Jupiter, Saturn, Uranus and Neptune, may still be in a primordial state and therefore hold the essential clues in our search to understand the formation of the solar system. It would be inefficient to send a spacecraft directly to one of these outer planets since the flight time before planetary encounter would be many years. To explore this region therefore requires a new approach in space exploration.

Multiplanet missions where the gravitational field of a planet is used to deflect the spacecraft trajectory so that it will reach a second planetary object are the best approach for the exploration of the outer solar system with our present technology. They have the advantage of reducing the total amount of fuel required for the mission, or the need for additional boosters.

The available spacecraft fall into three categories:

Mariner Class: Stabilised, high-data-rate remote sensing device which is most valuable as a sophisticated orbiter and fully developed (Plates 53, 55).

Pioneer Class: Cheap and a better load carrier than Mariner. Ideal as a probe carrier or as a low-cost orbiter. It is also fully developed (Plate 52).

Viking Class: A medium sized soft lander which is due to have its first flight to Mars in 1975 (Plate 51).

A further development would be a Mars surface sample return vehicle, but this has still to be studied in detail. With these tools, together with any Russian developments and the highly sophisticated space technology, we seem to be well placed to explore the planetary system. So what should be our strategy for the future?

In the past the philosophy has been to follow a sequence of flyby, orbiter and entry probe missions to a particular planet in order to identify the scientific problems and to provide a suitable rationale for answer-

Plate 50

Plate 50 The beautifully coloured Comet Humason (1961 e) photographed with the Hale Observatories 48-inch Schmidt Telescope (Courtesy of Hale Observatories)

INTERPLANETARY DUST

Classical ground-based attempts to recover cosmic dust — by the use of clean collecting surfaces, and the study of ocean sediment and polar ice cores — have been beset with contamination problems. The difficulties encountered here are illustrated by the estimates of micrometeorite flux rates for the Earth's surface per day from 10^6 to 10^{12} kg, depending on authority. In the last few years, laser ranging of the Earth's atmosphere has actually revealed dust concentrations in situ at heights from 80 to 100 km. Noctilucent Clouds, visible at this kind of height over high latitudes in the summer months, are thought to be caused by ice-crystals forming on this dust. Rocket flights have successfully collected particles in these clouds, and, as expected, many are either spherules or fluffy in nature, with compositions including chronditic and iron particles rich in heavy elements.

Artificial satellites offered the first opportunity to collect dust from outside the contaminating effects of the Earth's atmosphere. In general, however, the experiments have led to disappointing results. Examination of lunar rocks returned by the Apollo flights has proved to be a more reliable source of information on micrometeorite flux, especially on glassy surfaces. These studies have yielded excellent mass-distribution information and good space-density data. This work gave good confirmation of ground-based optical observations of the Zodiacal Dust Cloud, which had furnished much early basic information on the density and mass-distribution of the cloud.

A consideration of contemporary results leads to a fairly sound model for the interplanetary dust cloud, the mass range of cosmic dust clearly cannot extend downwards for ever, otherwise we would all be knee deep in fine flour. Indeed, the results from Pioneers 8 and 9 suggest a sharp cutoff at a mass of about 10^{-16} kg. The Zodiacal Cloud has a mass of about 3×10^{-16} kg, giving a space density of about 10^{-19} kg/cu.m or about 10 times the density of interstellar space. The cloud is losing some 10^8 kg/year, through fine particles being ejected outwards, larger particles spiralling inwards, and particles of all sizes being destroyed by erosive forces. The cloud would clearly dissipate quite rapidly, but it seems that periodic comets are able to supply enough fine dust to replenish the losses. Estimates suggest that comets Halley and Encke, the two most prominent periodic comets, have been contributing about 10^4 kg of material per second to the cloud for many centuries. This rough model will be clarified and extended to greater detail by the current extensive research.

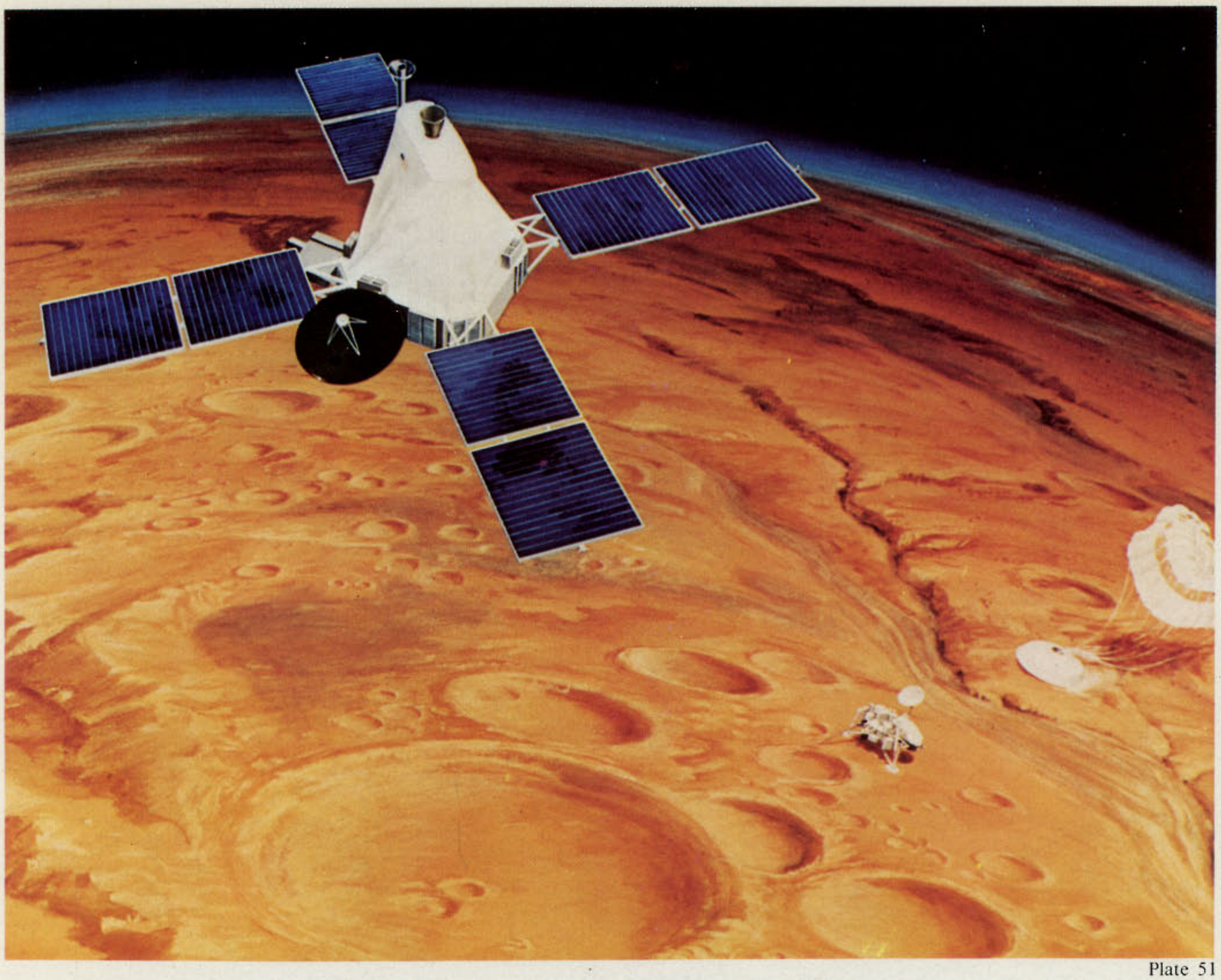

Plate 51

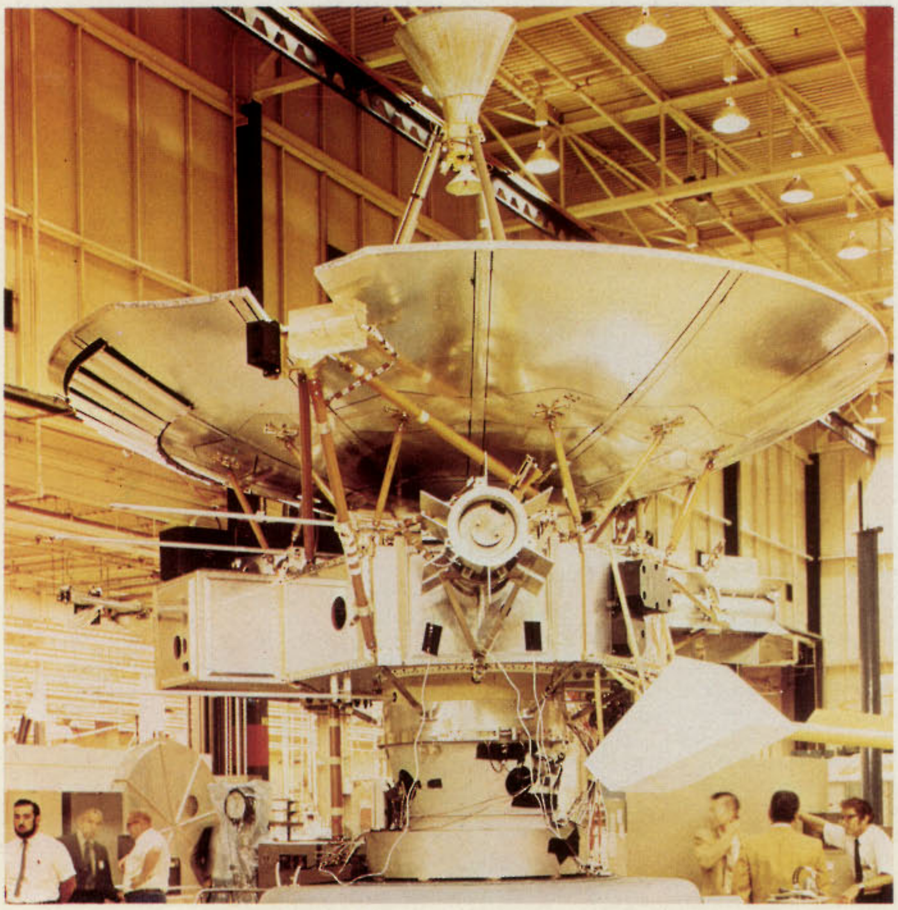

Plate 52

Plate 51 NASA plans to launch the Viking spacecraft to Mars in mid 1975 to arrive at the planet in July 1976. This painting is an impression of Viking in orbit about Mars with its life-searching lander below on the surface

Plate 52 The Pioneer F spacecraft undergoes vibration tests before the two Jupiter flights of Pioneers 10 and 11. Pioneer 10, almost miraculously, survived Jupiter's intense radiation belts to send back to Earth a wealth of new data on the planet

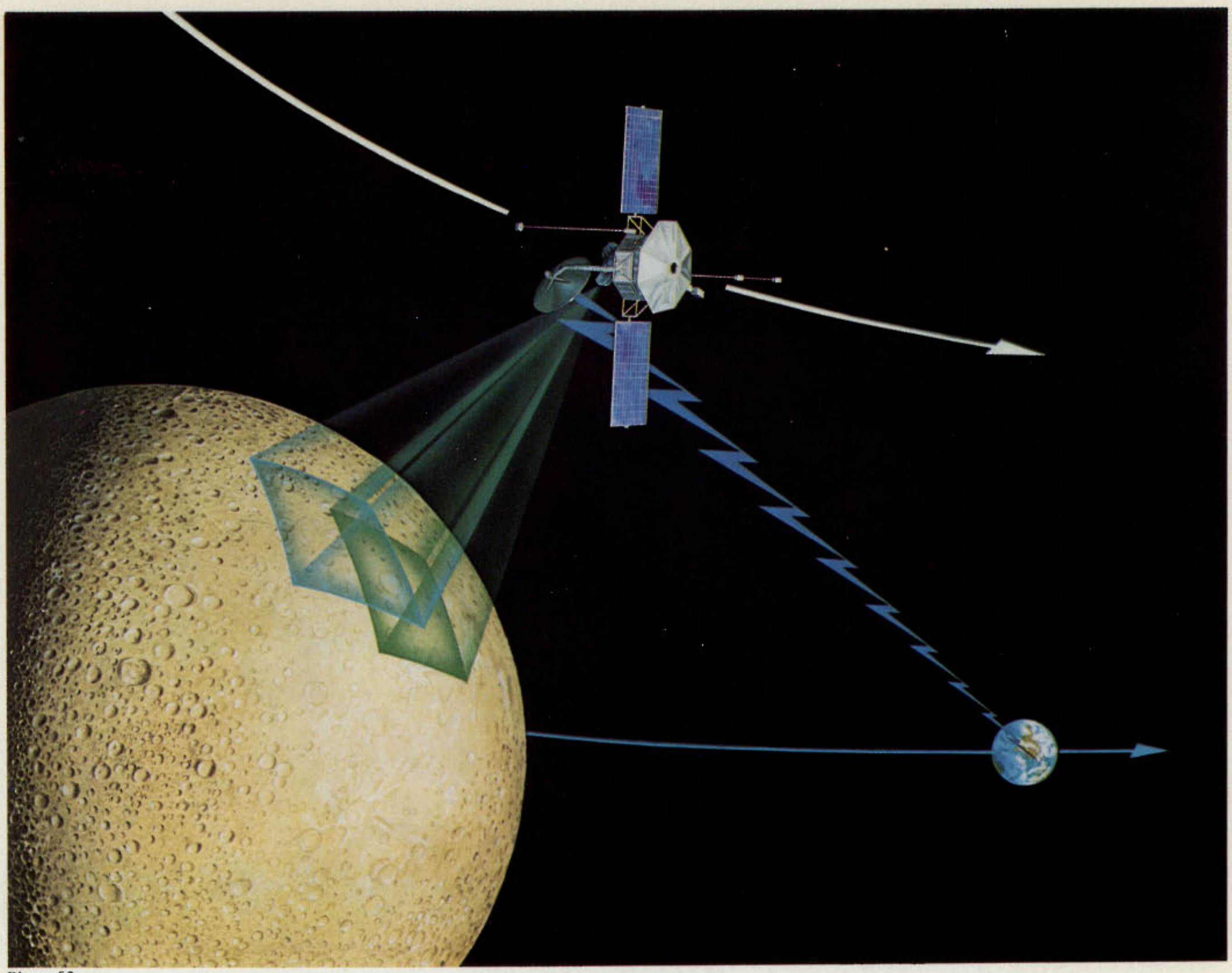

Plate 53

Plate 54

Plate 53 Artist's impression of Mariner 10 flying by Mercury and telemetering picture data to Earth. The first fly-by took place on 29 March 1974, the second Mercury encounter on 21 September. A third return seems likely in March 1975

Plate 54 This 64-m radio dish located near Madrid is part of NASA's, Deep Space Network which collects the data returned from spacecraft. NASA's other DSN stations are at Goldstone, California, and Canberra, Australia

Plate 55

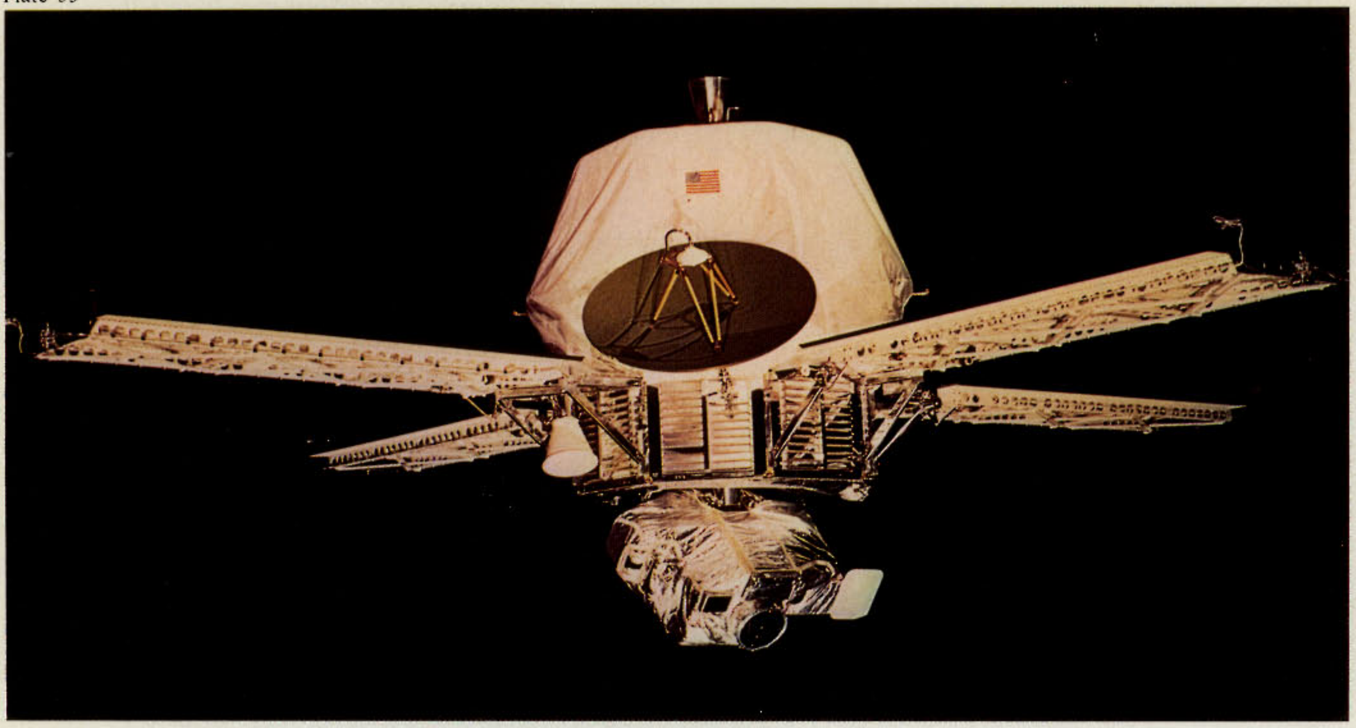

Plate 55 Mariner 9, the highly successful Mars orbiter which made 698 orbits of the planet during 1971 and 1972. Its twin TV cameras, mounted on the scan platform at the bottom of the spacecraft, returned a total of 7329 photos permitting planetologists to draw up the first detailed maps of Mars

THE MAJOR BODIES OF THE SOLAR SYSTEM

Body	Radius (Earth = 1)	Mass (Earth = 1)	Surface gravity (Earth = 1)	Mean density (g/cu.cm)	Escape velocity (km/s)	Period of rotation d	Period of rotation h	Period of rotation m	Inclination of equator to orbit	Mean distance from Sun (AU)	Sidereal period (years)
Sun	109·12	333000	28	1·41	—	25	09		7°·2	—	—
Mercury	0·382	0·055	0·38	5·44	4·2	58	16		0°·0	0·387	0·241
Venus	0·95	0·815	0·90	5·2	10·3	244	07		177°·8	0·723	0·615
Earth	1·00	1·000	1·00	5·52	11·2		23	56	23°·4	1·000	1·000
Moon	0·27	0·0123	0·17	3·34	2·3	27	07		1°·5	1·000	1·000
Mars	0·53	0·108	0·38	3·95	5·0		24	37	24°·0	1·524	1·881
Jupiter	11·18	317·8	2·58	1·34	61		09	50	3°·1	5·203	11·862
Saturn	9·42	95·15	1·07	0·7	37		10	14	26°·7	9·539	29·46
Uranus	3·84	14·54	0·9	1·58	22		10	49	97°·9	19·182	84·01
Neptune	3·93	17·23	1·2	2·3	25		15	48	28°·8	30·058	164·79
Pluto	0·5	0·17	0·2	—	—	6	09		—	39·439	247·7

THE PLANETARY SATELLITES

Planet	Satellite	Mean distance from primary (km × 10³)	Sidereal period (days)	Radius (km)
Earth	Moon	384	27·32	1738
Mars	Phobos	9	0·31	7
	Deimos	23	1·26	4
Jupiter	Io	422	1·77	1810
	Europa	671	3·55	1480
	Ganymede	1070	7·15	2600
	Callisto	1883	16·69	2360
	5	181	0·42	80
	6	11 476	250·6	50
	7	11 737	259·7	12
	8	23 500	739	10
	9	23 600	758	9
	10	11 700	259·2	8
	11	22 600	692	9
	12	21 200	630	8
	13	20 000?	—	—

Planet	Satellite	Mean distance from primary (km × 10³)	Sidereal period (days)	Radius (km)
Saturn	Mimas	186	0·94	270
	Enceladus	238	1·37	300
	Tethys	295	1·89	500
	Dione	377	2·74	480
	Rhea	527	4·42	650
	Titan	1222	15·95	2440
	Hyperion	1483	21·28	220
	Iapetus	3560	79·33	550
	Phoebe	12 950	550	120
	Janus	159	0·75	150
Uranus	Aerial	192	2·52	350
	Umbriel	267	4·14	250
	Titania	438	8·71	500
	Oberon	586	13·46	450
	Miranda	130	1·41	120
Neptune	Triton	355	5·88	1900
	Nereid	5562	260	120

ing the questions posed. But clearly, with the fiscal constraints of all governments, we cannot apply this procedure for all planets! However, the spacecraft that are presently available do possess some flexibility and it may therefore be possible to develop a multiplanet mission where an entry probe/orbiter is launched from the spacecraft at the first planetary encounter. Such an approach must be adopted if we are to obtain the maximum information from the fortunate alignments of the planets which occur during the next decade.

THE TERRESTRIAL PLANETS

The exploration of the inner solar system is, of course, by no means complete. The initial missions have raised issues leading to further explorations.

On Mars, the discovery of a meteorologically, geologically, and possibly biologically, active planet by Mariner 9 caused a dramatic revision of many previously held concepts. Indeed, the possibility of life on the planet has always been a driving force for Martian exploration.

A landing mission planned by the US in 1967. The spacecraft, known as Viking will be launched in August or September 1975. In orbit about the planet it will separate into two parts, an orbiter and a lander, which together will conduct studies of the Martian surface and atmosphere. One prime site is 19·5°N, 34°W in a region known as Chryse where several channel-like features, possibly the result of past water erosion, have been seen. A second site is in Cydonia at 44·3°N, 10°W. In winter this region is obscured by clouds in the north polar hood. It is believed that, at the season of the Viking landings, Cydonia will be a favourable location for the occurrence of water vapour and hence for conducting the biological experiments. While the lander is sampling the surface the orbiter will act as a relay station in the vital link to return information to the Earth.

What is the next step if the Viking exobiology experiment proves to be positive? Based upon lunar experience, the next logical step would be the return to Earth of a Martian surface sample. Opportunities for such a mission range from 1979 to the mid 1980's. But landing or sampling just a few areas of Mars does not give us a complete picture of the planetary surface. A further mission of considerable interest would be a post-Viking mission containing a surface rover on the lander which could therefore explore a considerable area of the planet. That would be a geologists dream!

In piecing together the history of the solar system recorded in the surface material we must keep Mercury within our sights. In its two fly-by encounters Mariner 10 has provided some startling pictures. It seems that the existence of large basins has now been recognised on the Moon, Mars and Mercury while these three bodies also exhibit striking asymmetries in their physiographic provinces. Is this a common aspect of terrestrial planet formation? Although, in total, only about 50 per cent of the surface has been viewed, there are many similarities between Mercury and the Moon. We are obviously interested in the bombardment histories of the two bodies, and the geological processes which shaped the face of Mercury. A third flyby is possible in 1975. A thorough assessment of the Mariner 10 data will indicate whether an orbiting mission is required to understand the surface morphology. But such a mission requires solar electric power which may not be available until about 1987.

Venus hides her surface beneath a veil of clouds. Although two Russian probes have reached the surface, we still do not understand the Venusian meteorology, the role of radiation in the deep atmosphere, the composition and structure of the clouds, or the surface morphology. A carefully balanced programme is necessary to obtain the information to answer these questions. NASA plans to launch two Pioneer class spacecraft in 1978 with the intention of studying these important scientific questions. One spacecraft will launch four probes toward different portions of the Venus surface and then enter the atmosphere itself, transmitting additional data before burning up. The second spacecraft will orbit the planet and investigate the regions of the atmosphere above the cloud tops. It is important that measurements are made by the descending probes from as high in the atmosphere as possible, since the Mariner 10 imaging experiment dramatically revealed the amazing motions in the Venus stratosphere. Observations in this tenuous portion of the atmosphere, are difficult but essential in understanding the driving mechanism(s). Tracking balloons floating at different pressure levels in the upper troposphere/lower stratosphere maybe the only way to unravel the complex atmospheric circulations which occur at these levels. But we shall have to wait until the 1980's at least for this type of experiment—unless of course the Russian's attempt it first!

THE MAJOR PLANETS

There is no doubt of the scientific importance of missions to the major planets. These huge, rapidly rotating, low-density planetary bodies, surrounded by extensive satellite systems, probably hold the key to our understanding of the formation of the solar system. Our strategy should be to make a detailed comparative study of the similarities and differences of these planets and their satellites. We are of course in our infancy with regard to exploring the outer regions of the solar system so it is important to examine the need to use flyby, orbiter and entry probes for each major planet, since we certainly cannot afford such an approach.

It would be unwise to consider a direct mission to each of the major planets. Such missions would have an extensive cruise period before reaching the primary object if it were Saturn, Uranus or Neptune, with the obvious danger of instrumental failure at the time the scientific study would commence. To reduce the flight times to planetary objects beyond 5 AU significantly requires advanced propulsion systems such as solar electric and nuclear electric; or alternatively, the space shuttle could be considered as a possible launch platform for missions in the 1980's and beyond.

With our present technological and scientific knowledge, multiplanet missions are the best approach for our exploration of the outer solar system. Jupiter is the key object in this approach since the planet's gravitational field can be used to deflect the spacecraft's trajectory and reduce the flight time to the planets beyond. In practice the assessment of this approach depended upon the (successful) result of the Pioneer 10 flyby demonstrating that a spacecraft could operate within the Jovian radiation belts.

The most exotic flyby missions conceived were those of the "Grand Tour", where two spacecraft launched in 1977, would fly by Jupiter-Saturn-Pluto, while the two launched in 1979 would fly by Jupiter-Uranus-Neptune. These missions were to exploit the unique alignment of the planets that exists during the 1970/80's. Regrettably the mission was considered to be too costly and cancelled. A Grand Tour of this type will not be

possible again for another 175 years.

The initial reconnaissance of the Jovian environment is being carried out by Pioneers 10 and 11. In 1979 the latter spacecraft will also take the first close-up look at Saturn, its rings, and search for any evidence of a magnetic field around the planet. The planetological programme will commence in 1977 with the Mariner-Jupiter-Saturn (MJS) mission. Besides magnetospheric investigations, Mariner's excellent remote sensing capability will be used to study the atmospheric phenomena of Jupiter, Saturn and Titan, and observe at close hand many of the satellites which surround the planets. By the early 1980's we shall be in a position to compare some of the properties of Jupiter and Saturn. But to extend our knowledge, particularly of the satellites, an orbiter mission is needed. A probe mission is also of fundamental importance if we are to determine precisely the abundance of the trace constituents of the Jovian atmosphere which are of cosmological importance. Our present knowledge is obtained by interpretative techniques which may result in model-dependent answers. A probe can provide invaluable information on the composition and structure of the clouds to improve remote sensing techniques for later missions. It would also be essential in resolving the present major difference between the temperatures in the upper Jovian troposphere observed by the Pioneer 10 occultation experiment, and those predicted by theory, if the dual-frequency occultation experiment on the MJS flyby does not provide the solution. To accomplish these objectives we need a technology in which probes to atmospheres of the many planets survive to a pressure level of at least 10 bars.

Both Mariner and Pioneer spacecraft would be suitable as Jupiter orbiters to make use of the best opportunity which occurs in 1981. The costs of a Pioneer Jupiter Orbiter could be minimised by using the existing Pioneer H spacecraft, and the mission should be devoted to an entry probe and magnetospheric studies. The planetological studies may then be carried out by Mariner with a launch in 1983, say, to utilise the wealth of information expected from MJS, in the planning of the new mission.

Magnetospheric studies of Jupiter require orbits with a periapsis of about 2R and apoapsis of 100R in the bowshock region covering at least four segments of the 360° longitude of the domain. The Galilean satellites, while major objects for study in their own right, could be used to deflect the spacecraft trajectory and provide orbits which satisfy these observational requirements. They may also be used to deflect the orbit out of the ecliptic plane to about 60° which would provide invaluable observations of the latitudinal properties of the atmosphere and magnetosphere. A Jupiter orbiter with this type of flexibility is obviously a major mission of the future. It would also provide a unique opportunity to study a "mini solar system" from a single mission.

It is possible to launch the first mission to Uranus in 1979, using a Mariner spacecraft and the gravitational field of Jupiter to deflect the trajectory. Favourable opportunities for Jupiter/Uranus missions recur at 12-year intervals. By 1985 the possible introduction of solar electric power should permit the orbiting of Saturn and bring Neptune within reach of a gravity-assisted mission.

To complete proposed inter-comparisons between the planets, a probe mission could be directed toward Saturn with possible launches in 1983, 1984, and to Uranus with a 1987 launch if the latter cannot be achieved earlier on the proposed Jupiter/Uranus fly-by mission. But without doubt, the most interesting object to explore by a probe mission is Saturn's large moon Titan (see page 48). This satellite of Saturn, which is as big as Mercury, may have an atmosphere as large as the Earth, layers of clouds, and may be harbouring elementary forms of life. A combined Saturn orbiter/Titan entry probe would make a scientifically exciting and rewarding mission.

Nineteen seventy four has therefore been a special and unusual year in man's history. In this period his knowledge of the planetary system has increased dramatically as a result of space exploration, and it has provided a stimulus for future missions which are necessary for us to understand fully the origin of the solar systems. We live in a scientifically exciting and rewarding era of planetary exploration.

EXOBIOLOGY

CARL SAGAN

Until the last half decade it was possible to wonder about life beyond the Earth but not to do very much about it. However, in 1969 the first samples were returned from another celestial object, revealing that the outer layers of the Moon were lifeless. This was in accord with almost everyone's speculations because the Moon — remarkably anhydrous, atmosphereless, and subject to fierce doses of ultraviolet and other solar radiation — seemed to be an inhospitable environment *par excellence*. And while there may be, for example, surface frost in permanently shaded regions near the lunar poles, it seems unwise to expect that future lunar exploration will uncover some cache of microbes.

We are now on the verge of the scientific exploration of much more interesting objects. Mars has been fabled as a possible abode for life — but largely for all the wrong reasons. The planet was early reported to have bright and dark markings, with the dark markings green; and it was not very difficult for 19th century writers to attribute the colouration to vegetation. But we now know that the dark areas of Mars, like the bright areas, are reddish, and that the greenish tint is a psychophysiological, rather than an astronomical, phenomenon. Each Martian spring and summer the contrast between adjacent bright and dark areas increases, a phenomenon which some 19th and 20th century observers attributed to the growth and proliferation of vegetation inhabiting the Martian dark areas. The Mariner 9 long time-baseline photography of the planet has shown, however, that these changes are almost certainly due to the redistribution of fine dust by very high winds on the planet, winds ranging between

Mach 0·1 and Mach 0·5 or higher.

Some 19th and 20th century naked-eye observers, particularly Percival Lowell, reported Mars to be covered by a network of rectilinear features which some thought to be the artificial constructions of a race of intelligent and thirsty Martians — a planet-wide water conservation project. Paul Fox and I at Cornell University have carefully studied the Mariner 9 photography of Mars — which covered the entire planet, pole-to-pole, at one-km resolution, a resolution one to two orders of magnitude superior to the best obtainable by ground-based telescopes — and are unable to find a single Lowellian "canal". There is a great rift valley, there are crudely linear ridges, there are occasional accidental alignments of impact craters. But there is no array of rectilinear features. The canals of Mars also appear to be psychophysiological rather than astronomical in origin.

From the apparent secular acceleration of the innermost Martian moon, Phobos, the Soviet astrophysicist I. S. Shklovskii proposed that the satellite was hollow — as is required for so large an object to be significantly dragged by the very thin Martian atmosphere at Phobos' altitude. Since there are no natural hollow objects, Shklovskii tentatively tendered the hypothesis that Phobos (and perhaps the other moon, Deimos, as well) was the construction of an extinct Martian civilisation of very great powers. The Mariner 9 photography of Phobos and Deimos reveal both to be old, cratered,

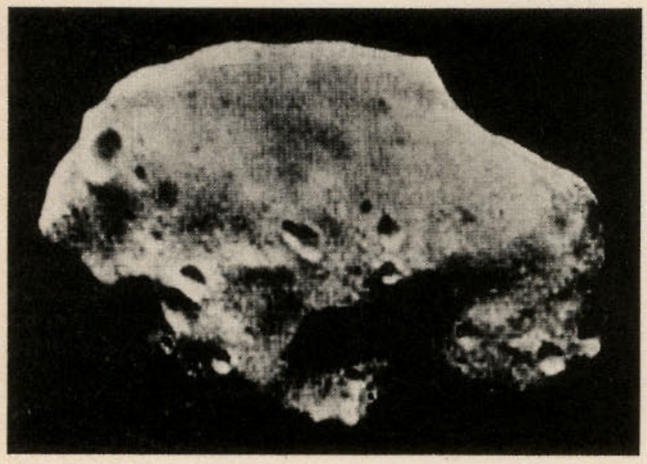

Figure 1 Mariner 9 took this close-up television picture of the Martian moon Phobos from a distance of 3444 miles. Far from being a hollow artefact constructed by intelligent Martians, as I. S. Shklovskii once imagined, Phobos is clearly a rocky chunk which has suffered many impacts in its long life, some of them by massive projectiles. Phobos is some 23 km long by 16 km wide and resembles an asteroidal body

impact-eroded and entirely natural objects approximately 4·5 thousand million years old. At the same time work by G. A. Wilkins and A. T. Sinclair in Britain seems to show that the apparent secular acceleration, which had been deduced by US celestial mechanicians, also does not exist.

Thus four of the most widely advertised "arguments" for life on Mars emerge in default, either because the observations were in error, or because alternative explanations of the observables have been found. This is not really very surprising. For one thing the great passions engendered by the search for life on another planet seem to produce arguments of considerably inferior rigour to those which are acceptable in other branches of science. This remark applies both to those promoting and those debunking the idea of life elsewhere in the solar system. For another thing, when the argument is turned around, and we imagine ourselves observing the Earth from the vantage point of Mars, life on Earth becomes elusive and subtle, at least in reflected light. At a surface resolution of 10 km — better than the best photographic or naked-eye telescopic observations of Mars from the Earth — our planet appears entirely lifeless. Individual organisms are too small to be seen, and the artefacts of our technical civilisation are likewise invisible. But when the resolution reaches about 100 m the Earth appears to crystallise out into an intricate patchwork quilt pattern (see Plate 18). This array of abutting squares and rectangles due to the activities of our urban and agricultural civilisation. Thus even if Mars had a civilisation of contemporary terrestrial extent and development, it would not have been detectable in reflected sunlight prior to the Mariner 9 mission (1971-1972).

ENIGMATIC FEATURES

As well as photographing all of the planet at km resolution, Mariner 9 observed a few per cent of the planet at 100 m resolution, an adequate resolution and surface coverage to have detected life on Earth. No compelling evidence for Martian biology emerges from a study of the Mariner 9 photography. The most enigmatic feature is an array of long bright linear features on the great Tharsis plateau area, which are remarkable because they are unconnected with craters. There are bright streaks on many places of the planet, but almost all of them emerge from craters, and are thought to have been produced by the deflation of fine dust from the crater interiors. But sources of dust other than crater interiors can be imagined.

Likewise there is a remarkable set of pyramidal mountains a few km across the base and perhaps one km high. It is possible that these features are large-scale Martian ventifacts — objects which erode in a faceted or polyhedral geometry because of the fracture planes of the material and the prevailing wind directions. Because the Martian atmosphere is so thin, the wind speeds required to move particles there are much higher than on Earth. The efficiency of aeolian abrasion depends on a relationship lying between the cube and the fifth power of velocity. Accordingly aeolian abrasion should be much more effective and should extend to much higher altitudes on Mars than on the Earth. Apart from these few objects nothing appears on the Mariner 9 photography which is even remotely suggestive of the presence of life on the planet.

What then are the prospects for life on Mars? I think we must conclude that we have far too little evidence to decide one way or another. The Martian physical environment is harsh by some terrestrial standards. But even so there are many terrestrial micro-organisms which can survive indefinitely under Martian ambient conditions. Growth of terrestrial inoculants in simulated Martian environments occurs when there are small quantities of liquid water available. In one experiment interstitial water was available for only 15 minutes a day and inoculants replicated during that 15 minutes, producing a very regular step-function growth curve.

Water and ultraviolet light are certainly important boundary conditions for possible life on Mars. Even if hypothetical Martian genetic material were as ultraviolet-labile as the nucleic acids, it is easy to imagine adaptations to the high ultraviolet flux on Mars. The Martian surface material is extremely opaque to solar ultraviolet radiation. Martian organisms could easily

protect themselves by carrying around an iron-rich siliceous shell, or by hiding under small rock fragments. The total atmospheric pressure on Mars is below the triple point of the water phase diagram. But high-altitude infrared aircraft observations of Mars have shown the widespread presence of mineral hydrates on the planet. In fact, it appears that the Martian surface material, down to a depth of at least metres, is composed of 1 per cent physically and chemically bound water. The bonding energy is very low — only a few electron volts per bond — and it is entirely conceivable that Martian organisms can tap this abundant water source. If so the red deserts of Mars may be for Martian organisms an ocean.

Perhaps the most enigmatic finding by Mariner 9 was that the Martian surface has thousands of sinous tributaried braided channels, a few more than 1000 km long. It seems now impossible to avoid the conclusion that at least some of these channels have been produced by running water. In some cases the water has an internal origin —as, for example, when a "thermokarst" is produced from the geothermal melting of large quantities of ground ice. But many other channels, particularly those with tributaries, seem able to be produced only by rainfall. The dating of the events which produced the channels from the curves relating impact-crater diameters to their frequency is a very difficult task because there are so few craters in the channels. Preliminary results by David Pieri of Cornell University and William K. Hartmann of the Planetary Sciences Institute, Tucson, Arizona, suggest, though, that at least many of the channels are no younger than 100 million years — but many small channels may have held water more recently. The existence of water channels on Mars when there can be no liquid water today, as well as the laminated terrain in the Martian polar regions, points to the possibility of substantial climatic variations during Martian history. If the Martian environment was once rich, with gurgling brooks and mightily coursing rivers, the chances of life on Mars, at least in the eyes of liquid water chauvinists, is substantially increased. It is even possible that lying in cryptobiotic repose on Mars are micro-organisms awaiting the end of the long drought.

THE COMING SEARCH FOR LIFE

In the summer of 1976 two American spacecraft called Viking are scheduled to land on Mars and there attempt to search directly for life. There are three experiments which involve metabolic studies of possible Martian microbes acquired by an automated sample arm. Two of the experiments are wet and one is dry, providing — if the experiments work — initial tests for both conceivable water metabolisms, wet and dry, of hypothetical Martian microbes. There is also a mass spectrometer-gas chromatograph which, at least under some circumstances, might be able to distinguish meteoritic and prebiological organic chemistry from biological organic chemistry. And, finally, there are two television cameras which can recognise large Martian organisms, if they exist, independent of their metabolism.

In scientific speculation about Mars one finds an interesting tendency to consider microbial life possible but larger organisms — those I call macrobes — extremely dubious. I have never found any arguments in favour of this thesis and prefer to consider open the question of large plants and animals on the Martian surface.

Viking should not be considered a definitive test for life on Mars. I believe it is a creditable first attempt. But it is possible that Mars is covered with micro-organisms constructed on principles different from those for which the Viking biology package is designed to search. Because microbial exobiology instrumentation has never before been flown in spacecraft, it is possible that the performance of these instruments will be less than optimal. But, at the very least, we are on the verge of the first serious scientific investigation of another planet for indigenous life.

BEYOND MARS

In the longer term the clear exobiological objectives besides Mars lie in the outer solar system. Jupiter, Saturn, Uranus, Neptune and Saturn's largest moon, Titan, have atmospheres rich in hydrogen and other reducing gases similar to the atmosphere of the Earth at the time of the origin of life. In experiments which B. N. Khare and I have performed at Cornell, such atmospheres are simulated and irradiated with long-wavelength ultraviolet light. The products are circulated through a bath of aqueous ammonia as is likely to exist in the clouds of the Jovian planets. We produce in high yield, in the gas, liquid, and solid phases, a wide variety of molecules — including more than 40 amino acids, the building blocks of proteins. The solid phase polymeric material produced in such experiments has optical properties entrancingly similar to those of the reddish-brown clouds of Jupiter, Saturn and Titan. Indeed the rate of ultraviolet production of such optically opaque organic material on Jupiter, combined with the estimated destruction rate of such molecules by turbulent diffusion to depths where heat would destroy them, yields a steady-state abundance of polymers comparable to the observed abundance of chromophores responsible for the Jovian colouration.

It may be that the Jovian planets are vast world-sized laboratories for prebiological organic chemistry. While this obviously remains a much more speculative proposition, it seems perfectly possible that these environments — in which food is falling from the skies like manna from heaven, and in which warm aqueous clouds are present in great abundance — may be of interest to the biologist as well as to the organic chemist. The speed of free fall of small organisms on Jupiter is sufficiently slow for there to be more than enough time for such hypothetical organisms to reproduce before reaching pyrolytic depths. It is even possible to imagine larger balloon-like organisms in the Jovian clouds which work either because they have actively pumped helium out or because they have, through metabolic heating, become warmer than their surroundings.

The Mariner-Jupiter-Saturn missions will be launched in 1977 and will arrive near Jupiter in 1979, and near Saturn and Titan in 1981. They are the first experiments which can be expected to shed significant light on these problems. These are fly-by spacecraft only, but they are equipped with high-resolution ultraviolet and infrared spectroscopy, as well as high-resolution imaging systems equipped with narrow-band filters. The detailed chemical make-up, small-scale distribution and time-evolution of the coloured materials on these planets may be forthcoming by the turn of the decade. After that there is the very exciting prospect of entry probes to do *in situ* organic chemistry in the atmospheres of the Jovian planets and Titan. The first exobiological reconnaissance of the solar system is just around the corner.

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